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Am J Physiol Renal Physiol 292:361-372, 2007. First published Aug 1, 2006;
doi:10.1152/ajprenal.00207.2006

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Renal expression of organic anion transporter OAT2 in rats and mice is regulated by sex hormones

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Submitted 8 June 2006; accepted in final form 27 July 2006

Ljubojević M, Balen D, Breljak D, Kušan M, Anzai N, Bahn A, Burckhardt G, Sabolić I. Renal expression of organic anion transporter OAT2 in rats and mice is regulated by sex hormones. *Am J Physiol Renal Physiol* 292: F361–F372, 2007. First published August 1, 2006; doi:10.1152/ajprenal.00207.2006.—The renal reabsorption and/or excretion of various organic anions is mediated by specific organic anion transporters (OATs). OAT2 (Slc22a7) has been identified in rat kidney, where its mRNA expression exhibits gender differences [females (F) > males (M)]. The exact localization of OAT2 protein in the mammalian kidney has not been reported. Here we studied the expression of OAT2 mRNA by RT-PCR and its protein by Western blotting (WB) and immunocytochemistry (IC) in kidneys of adult intact and gonadectomized M and F, sex hormone-treated castrated M, and prepubertal M and F rats, and the protein in adult M and F mice. In adult rats, the expression of OAT2 mRNA was predominant in the outer stripe (OS) tissue, exhibiting *1*) gender dependency (F > M), *2*) upregulation by castration and downregulation by ovariectomy, and *3*) strong downregulation by testosterone and weak upregulation by estradiol and progesterone treatment. A polyclonal antibody against rat OAT2 on WB of isolated renal membranes labeled a ~66-kDa protein band that was stronger in F. By IC, the antibody exclusively stained brush border (BB) of the proximal tubule S3 segment (S3) in the OS and medullary rays (F > M). In variously treated rats, the pattern of 66-kDa band density in the OS membranes and the staining intensity of BB in S3 matched the mRNA expression. The expression of OAT2 protein in prepubertal rats was low and gender independent. In mice, the expression pattern largely resembled that in rats. Therefore, OAT2 in rat (and mouse) kidney is localized to the BB of S3, exhibiting gender differences (F > M) that appear in puberty and are caused by strong androgen inhibition and weak estrogen and progesterone stimulation.

androgens; estrogens; gender differences; kidney; membrane transporters; progesterone; organic anion; transporter-2

PROCESSES OF reabsorption, distribution, and elimination of endogenous and xenobiotic organic anions (OA) in the mammalian liver and kidney are mediated by the multispecific OA transporters (OATs; subfamily of Slc22 drug transporters) that reside in the apical or basolateral membrane of epithelial cells (reviewed in Refs. 9, 18, 36, 46, 48, 52, 53, 55–57). In humans and experimental animals, the rate of renal excretion of many OA exhibits gender differences, which, at least in rodents, can be correlated with the sex-dependent expression of relevant OATs at the level of mRNAs and/or proteins (6–8, 10, 19, 21, 27, 29, 32, 37, 41, 46, 47, 49, 54, 55).

OAT2 (Slc22a7) was originally cloned from the rat liver cDNA as novel liver-specific transporter (NLT) (50), later renamed OAT2 (48). The rat ortholog of OAT2 (rOAT2) consists of 535 amino acid residues, with intracellular COOH and NH_2 terminals and two possible N-glycosylation sites (50), and exhibits 87 and 79% identity to mouse (mOAT2) (27) and human OAT2 (hOAT2) (50) as well as 42 and 39% homology to rOAT1 (48) and rOAT3 (30), respectively. When expressed in *Xenopus laevis* oocytes or cultured cells, rOAT2 mediated the Na^+-independent transport of salicylate, acetylsalicylate, prostaglandin E_2, α-ketoglutarate, methotrexate, and (weakly) *p*-aminohippuric acid (PAH), whereas hOAT2 and mOAT2 did not transport salicylate, indicating subtle species differences in the substrate specificity (27, 48, 51). The human and rat OAT2 may also transport some prostaglandins, cephalosporin antibiotics, and some other chemotherapeutics (9, 13, 22, 36). The driving force(s) for OAT2-mediated transports has not been clearly resolved; although recently claimed to be an OA/dicarboxylate (fumarate, succinate) exchanger (26), its definition as an anion exchanger or facilitator is still disputable.

In rats, mice, and humans, the OAT2-specific mRNA is principally expressed in liver and kidney, showing somehow contradictory data regarding its level in different species and studies. In rats, a low level of rOAT2 expression was detected in fetal time and before puberty (<40 days of age) in both organs (6, 50), whereas in adult animals, the expression in male (M) and female (F) kidney was found to be either lower (50) or higher (6, 27) than in liver. The rOAT2 expression in kidney exhibited strong gender differences (F > M), possibly due to growth hormone-mediated inhibitory action of androgens (6, 7, 24, 29). In mice, mOAT2 expression was also low in the fetal and prepubertal period (8, 39), whereas in sexually mature animals, the expression in kidney was found to be either much lower (39) or much higher (8, 27) than in liver; gender differences were observed in liver (F > M) by Kobayashi et al. (27) but not by Buist and Klaassen (8) and not in kidney (8, 27). In humans, hOAT2 appears in two alternatively spliced forms (hOAT2A and hOAT2B) showing different COOH-terminal sequences that are expressed more in liver than kidney (51).

While the rOAT2 protein [relative molecular mass (M_r) ~62 kDa] in the rat liver cells was immunolocalized to the sinusoidal membrane (50), the exact localization of this transporter in the mammalian kidney is still controversial. In the study by

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Kojima et al. (28), rOAT2 was identified as the ~60-kDa protein equally distributed in the cortical, outer medullary and inner medullary tissue and immunolocalized to the apical membrane of thick ascending limb of Henle (TALH) and cortical and medullary collecting ducts (CD) in the rat kidney, whereas hOAT2 was immunolocalized to the proximal tubule basolateral membrane in the human kidney (13). In the mouse kidney, mOAT2 was recently localized to the luminal membrane of proximal tubules in the M animal (25). In this work, we reinvestigated expression of the rOAT2-specific mRNA in the kidneys of M, F, and variously treated M rats by RT-PCR and performed a detailed immunolocalization of this transporter along the rat and mouse nephron by using an affinity-purified, polyclonal anti-peptide antibody that reacted with OAT2 in both species.

MATERIAL AND METHODS

Animals and treatment. Prepubertal (age: 20–25 days), young (age: 6 wk), and adult (age: 11–12 wk) M and F Wistar strain rats were from the breeding colony at the Institute in Zagreb. Animals were bred and maintained according to the Guide for Care and Use of Laboratory Animals (National Research Council). Before and during experiments, animals had free access to standard pelleted food and tap water. The studies were approved by the Ethics Committee of the Institute of Medical Research and Occupational Health.

Prepubertal rats were used intact, and young M rats were sham operated or gonadectomized, whereas adult rats were used either intact, sham operated, or gonadectomized. M rats were castrated by a scrotal route, whereas F rats were ovariectomized by the dorsal (lumbal) approach under proper anesthesia [Narketan (80 mg/kg body mass)-Xylapan (12 mg/kg body mass), ip]. The sham-operated animals underwent the same procedure, except the respective organs were not removed.

The castrated, ovariectomized, and sham-operated adult rats were left to recover for 4 wk before death. The young M rats were castrated or sham operated; 6 wk later, the castrated animals underwent a subcutaneous treatment with either testosterone enanthate or estradiol dipropionate, or progesterone at a dose of (each) 2.5 mg·kg body mass^{-1}·day^{-1} for 14 days. The hormones were injected as a sunflower oil solution. The castrated control and sham-operated rats were treated with an equivalent amount of sunflower oil (0.5 ml·kg body mass^{-1}·day^{-1} for 14 days).

Antibodies and other material. An immune serum against the peptide sequence in the COOH-terminal domain of the protein (amino acids 512–528: ETKKAQLPETIQDVERK), which is common to rOAT2 (GenBank: NP_445989.1 for *Rattus norvegicus*) and mOAT2 (GenBank: NP_659105.1 for *Mus musculus*), was raised in rabbits, and the antibody (rOAT2-Ab) was purified using an affinity column. Compared with the previously described antibody (28), the rOAT2-Ab used in the present study was *1*) raised against the same peptide sequence but in different rabbits showing higher antibody titer following immunization (ELISA data not shown) and *2*) tested by an optimized processing of isolated membranes in Western blotting experiments and antigen retrieval technique in tissue cryosection (see below). The antibody was kindly supplied by Transgenic, Kumamoto, Japan. The use of affinity-purified polyclonal antibodies for Na-K-ATPase and water channel aquaporin-1 (AQP1) was described in our previous publications (42, 44). A monoclonal antibody against α-actin was purchased commercially (Chemicon International, Temecula, CA). Secondary antibodies, including the CY3-labeled (GARCY3) and alkaline phosphatase-labeled goat anti-rabbit (GARAP) or anti-mouse IgG (GAMAP) antibodies, were purchased from Jackson ImmunoResearch Laboratories, (West Grove, PA) or Kirkegaard and Perry (Gaithersburg, MD).

Anesthetics (Narketan and Xylapan) were purchased from Chassot, Bern, Switzerland. Oil solutions of testosterone enanthate, estradiol dipropionate, and progesterone were from RotexMedica (Trittau, Germany) and Galenika (Belgrade, SCG). The reagents and kits for RNA isolation and RT-PCR were obtained commercially; RNALater was from Sigma-Aldrich (Taufkirchen, Germany), Trizol and DNase/RNase-free water were from Gibco-BRL (Grand Island, NY), First Strand cDNA Synthesis Kit was from Fermentas International (Burlington, ON, Canada), whereas custom primers for rOAT2 and β-actin were from Invitrogen (online). Various other chemicals were of the highest purity available and were purchased from either Sigma (St. Louis, MO) or Fisher Scientific (New Jersey, NJ).

Isolation of RNA and RT-PCR. The animals were killed by decapitation. The kidneys were removed, decapsulated, and cut into 1-mm-thick sagital slices. One slice was immediately submerged into the RNAlater solution for manual separation of the cortical and outer stripe tissues. Total cellular RNA from these zones was extracted using Trizol according to the manufacturer's instructions. RNA concentration and its purity were estimated by spectrophotometric measurement of the optical density at 260/280 nm. The quality and integrity of RNAs were tested by agarose gel electrophoresis. Isolated RNAs were stored at −70°C until use. To perform RT-PCR, first-strand cDNA synthesis was performed using the First Strand cDNA Synthesis Kit following the prescribed instructions. Total cellular RNA (3 μg) was denatured at 70°C for 5 min in reaction mixture containing 0.5 μg oligo(dT)$_{18}$ and reverse transcribed in a total volume of 20 μl of reaction mixture containing 1× reverse transcription buffer, 20 units of ribonuclease inhibitor, 1 mM dNTPmix, and 40 units of Moloney murine leukemia virus (M-MuLV) RT. The reaction mixture was then incubated at 37°C for 60 min, followed by incubation at 72°C for 10 min. cDNAs were diluted 5× in DNase/RNase-free water and stored at −20°C until use. PCR was performed in total volume of 20 μl using 1 μl of 5×-diluted first-strand cDNA, 0.4 μM rOAT2-specific primers, and ready-to-use PCR Master Mix, following instructions from the manufacturer. The housekeeping gene β-actin was used as a control for variations in the input of RNA. The sequences of specific forward and reverse rOAT2 and β-actin primers used for RT-PCR reactions, and predicted RT-PCR product sizes, are listed in Table 1. To avoid amplification of genomic DNA, the intron overspanning primers were used. The reaction conditions used for

Table 1. *Primer sequences used for RT-PCR*

Forward and Reverse Primers (5′-3′)	GenBank Accession No.	Location	RT-PCR Product Size, bp
	rOAT2		
F: CGCTCAGAATTCTCCTCCAC	NM_053537.1	434–453	311
R: ACATCCAGCCACTCCAACTC		725–744	
	β-*Actin*		
F: GTCGTACCACTGGCATTGTG	NM_031144.2	518–537	364
R: AGGAAGGAAGGCTGGAAGAG		862–881	

Genes: rat ortholog of organic anion transporter-2 (rOAT2) and β-actin. F, forward; R, reverse.

PCR were as follows: initial denaturation for 3 min at 94°C, denaturation for 30 s at 95°C, annealing for 30 s at 95°C, and elongation for 45 s at 72°C, with 32 and 30 cycles for OAT2 and β-actin, respectively. The nontemplate control (NTC) reactions, where the cDNA was substituted with DNase/RNase-free water, were included in each PCR reaction to screen for possible contamination; no PCR products were detected in NTC reaction, indicating the absence of possible contamination (data not shown). RT-PCR products were resolved by electrophoresis in 1% agarose gel, stained with ethidium bromide, and visualized under ultraviolet light. To obtain quantitative results, preliminary experiments were done to determine the optimal number of PCR cycles within the exponential phase of the PCR reaction (data not shown).

Tissue fixation and immunocytochemistry. The animals were anesthetized, and the circulatory system was perfused via the left ventricle of the heart using the Masterflex pump (Cole-Parmer, Chicago, IL), first with aerated (95% O_2-5% CO_2) and temperature-equilibrated (37°C) phosphate-buffered saline (PBS; in mM: 137 NaCl, 2.7 KCl, 8 Na_2HPO_4, 2 K_2PO_4, pH 7.4) for 2–3 min to remove blood, and then with 10 ml (mice) or 150 ml (rats) of fixative (4% paraformaldehyde in PBS) for 4–5 min. The kidneys were removed, sliced, and kept overnight in the same fixative at 4°C, followed by extensive washing in PBS and storage in PBS containing 0.02% NaN_3 at 4°C until further use.

To cut 4-μm frozen sections, tissue slices were infiltrated with 30% sucrose (in PBS) overnight, embedded in the Jung Tissue Freezing Medium (Leica Microsystems, Nussloch, Germany), frozen at −25°C, and sectioned in a Leica CM 1850 cryostat (Leica Instruments, Nussloch, Germany). Sections were collected on Superfrost/Plus Microscope slides (Fischer Scientific), dried at room temperature for 2–3 h, and kept refrigerated until further use.

An antigen retrieval technique was used to maximize the antibody-binding sites. In preliminary studies, we tried different methods to process tissue cryosections before immunostaining, including *1*) pretreatment without or with ionic (SDS) or nonionic detergents (Triton X-100) that were previously used to reveal cryptic Na-K-ATPase and vacuolar H^+-ATPase (5, 43), *2*) pretreatment with xylol and graded concentrations of ethanol (steps used for antigen retrieval in paraffin sections) without or with microwave heating in citrate buffers of different pH that were found to be optimal for revealing OAT1 and OAT3 in the rat kidney (32), and *3*) pretreatment with microwave heating only in citrate buffers of different pH, 3, 6, or 9, without or with 0.5% Triton X-100. The immunostaining efficiency following these procedures was very heterogeneous (data not shown). The following procedure gave the strongest immunostaining of OAT2 in the rat and mouse cryosections: sections were rehydrated in PBS for 15 min, heated in 10 mM citrate buffer, pH 6, in a microwave oven (4 cycles, 5 min each at 800 W), followed by cooling down to room temperature in the same buffer for 20 min. Further steps were performed in a wet chamber: sections were incubated with 0.5% Triton X-100 (in PBS) for 5 min, rinsed with PBS (5 × 5 min each), incubated for 20 min with bovine serum albumin (1% BSA in PBS) to block the nonspecific antibody binding, incubated with the rOAT2-Ab (diluted 1:2,000 with PBS) overnight in a refrigerator, rinsed with PBS (4 × 5 min each), incubated with GARCY3 (1.6 μg/ml in PBS) at room temperature for 60 min, rinsed with PBS (4 × 5 min each), and mounted in a fluorescence fading retardant (Vectashield; Vector Laboratories, Burlingame, CA).

To test the staining specificity, rOAT2-Ab was blocked with the immunizing peptide (final concentration of the peptide, 0.5 mg/ml) for 4 h at room temperature before use in the above-described immunofluorescence assay.

The stained sections were examined and photographed with an Opton III RS fluorescence microscope (Opton Feintechnik, Oberkochen, Germany) using a Spot RT Slider camera and software (Diagnostic Instruments, Sterling Heights, MI). The photos were imported into Adobe Photoshop 6.0 for processing and labeling.

Preparation of tissue homogenates and membranes. Animals were killed by decapitation. Mouse kidneys were used in toto. Rat kidneys were removed and sagitally sliced, and their cortex and outer stripe were dissected manually and used as separate tissue pools, while the inner stripe and inner medulla were processed as a single sample. The respective tissue was homogenized (10% homogenate) in a chilled buffer (in mM: 300 mannitol, 5 EGTA, 12 Tris·HCl, pH 7.4, 1 phenylmethylsulfonyl fluoride, and 0.1 benzamidine and 0.1 μg/ml antipain) with a Powergen 125 homogenizer (Fisher Scientific) at maximal setting (1-min homogenization, 1-min pause, 1-min homogenization). The total cell membranes (TCM) were isolated from the homogenate by first removing cell debris by centrifugation in a refrigerated high-speed centrifuge (Sorvall RC-5C; Sorvall Instruments, Newtown, CT; rotor SS34) at 6,000 *g* for 15 min. The pellet was discarded, and the supernatant was then centrifuged at 150,000 *g* for 1 h (ultracentrifuge Sorvall OTD-Combi, rotor T-875). The final pellet (TCM) was resuspended in homogenizing buffer.

The homogenates of cortical and outer stripe tissues of the rat kidney and the whole mouse kidney homogenates were used to isolate brush-border membranes (BBM) by Mg^{2+}-EGTA precipitation (1). After dispersion of membranes in an appropriate volume of buffer (150 mM mannitol, 6 mM EGTA, 6 mM HEPES-Tris, pH 7.4) and measurement of proteins by the Bradford assay (2), all membrane preparations were stored at −70°C until further use for immunoblotting studies.

SDS-PAGE and Western blotting. The membrane samples were thawed at 37°C and mixed with sample buffer, which in a final mixture contained the following: 1% SDS, 12% vol/vol glycerol, 30 mM Tris·HCl, pH 6.8, without (nonreducing conditions) or with 5% β-mercaptoethanol (β-ME; reducing conditions). Samples were denatured at 95°C for 5 min, 65°C for 15 min, or 37°C for 30 min. Proteins were separated through 10% SDS-PAGE minigels using the Vertical Gel Electrophoresis System and then electrophoretically wet-transferred using a Mini Trans-Blot Electrophoretic Transfer Cell (both Bio-Rad Laboratories, Hercules, CA) to an Immobilon membrane (Millipore, Bedford, MA). The amount of protein per lane was 30–40 μg for BBM and 60–80 μg for TCM; the exact amount of protein per lane is indicated in figure legends. Following transfer, the Immobilon membrane was briefly stained with Coomassie Brilliant Blue to check for the efficiency of transfer, destained, blocked in blotting buffer (5% nonfat dry milk, 0.15 M NaCl, 1% Triton X-100, 20 mM Tris·HCl, pH 7.4), and incubated at 4°C overnight (12–14 h) in the same buffer containing either rOAT2-Ab (1:2,000), anti-Na-K-ATPase antibody (1:1,000), or anti-AQP1 antibody (1:10,000). In some experiments, to check for proper loading and transfer, the lower part of the stained transfer membrane was cut off, destained, blocked in blotting buffer, and probed for α-actin by incubation at 4°C overnight in the anti-α-actin antibody (1:1,000 in blotting buffer). Then the membranes were washed with blotting buffer (4 × 15 min), incubated for 60 min in the same buffer that contained GARAP (0.1 μg/ml) or GAMAP (0.5 μg/ml), washed again, and stained for alkaline phosphatase activity using the color-developing assay that contained 5-bromo-4-chloro-3-indolyl phosphate (BCIP; 1.65 mg/ml) and nitro blue tetrazolium (NBT; 3.3 mg/ml) in 20 mM Tris·HCl buffer, pH 9.0.

The labeled rOAT2-related protein band, estimated at ~66 kDa by use of commercial protein markers (Gibco-BRL), was evaluated by densitometry. The intensity of the labeled band was scanned (Ultroscan Laser Densitometer; LKB, Bromma, Sweden), and the integrated surface of each scan was expressed in arbitrary units, relative to the strongest band density (=1,00 unit) in the corresponding control samples.

Presentation of the data. The RT-PCR data were obtained with RNA preparations from two animals of each experimental group, whereas the immunocytochemical and immunoblotting data represent findings in four to five animals in each experimental group. The numeric data, expressed as means ± SE, were statistically evaluated

by use of Student's *t*-test or ANOVA with Duncan's test at the 5% level of significance.

RESULTS

Expression of OAT2-specific mRNA in rat kidney. Previous studies with various methods, including Northern blotting, branched DNA analysis, and RT-PCR, described gender differences in the renal expression of rOAT2 (F > M) in sexually matured rats (6, 7, 24, 29). Following castration in M rats, the rOAT2 transcript in the kidney was either upregulated (24, 29) or unchanged (7), and the treatment of castrated M with testosterone or estrogen downregulated, whereas ovariectomy in F either had no effect (29) or slightly downregulated (7), the renal rOAT2 expression. Although partially contradictory, overall these data indicate that gender differences in the renal expression of rOAT2 mRNA in rats might be caused by androgen inhibition and estrogen stimulation. To reinvestigate these data, we have isolated RNA from the kidney outer stripe tissue (it exhibits the highest expression of rOAT2 protein; see below) of sham-operated and gonadectomized M and F rats, and of castrated M treated with oil (control) or various sex steroids, and compared the rOAT2-specific mRNA expression by RT-PCR (Fig. 1).

As shown in Fig. 1*A*, the sham-operated F exhibited a higher expression of rOAT2 mRNA than the sham-operated M, proving the presence of gender differences (F > M). Castration upregulated, whereas ovariectomy downregulated, the rOAT2 mRNA expression, indicating that androgens acted inhibitory and estrogens stimulatory. These findings were further confirmed by treating castrated M with testosterone, which resulted in downregulation, and with estradiol or progesterone,

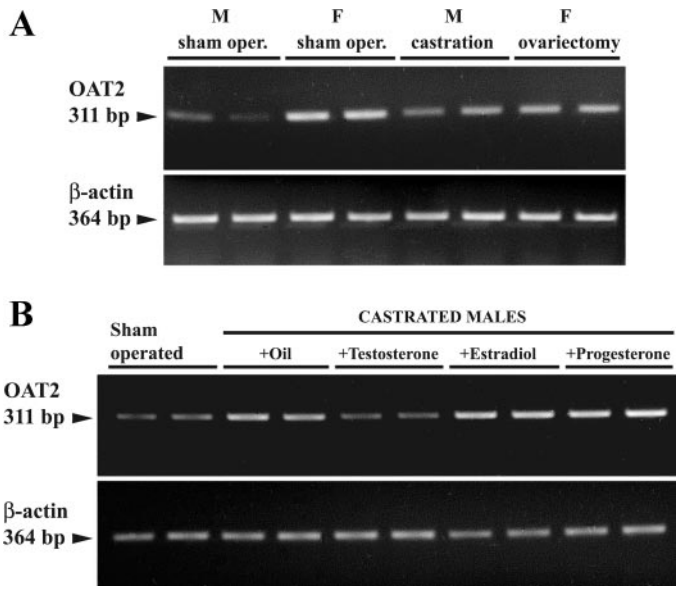

Fig. 1. RT-PCR data showing the expression of rat organic anion transporter-2 (rOAT2)- and β-actin-specific mRNAs. *A*: the kidney outer stripe tissue of sham-operated and gonadectomized male (M) and female (F) rats. *B*: the castrated M treated with oil (control) or various sex hormones. Each band represents mRNA expression in the tissue from a separate animal. The data prove gender differences in the renal OAT2 mRNA expression (F > M), its upregulation by castration and downregulation by ovariectomy (*A*), and its downregulation by testosterone and upregulation by estradiol and progesterone treatment (*B*). The expression of β-actin mRNA was similar in renal tissues from both sexes and remained unaffected by the hormonal treatment.

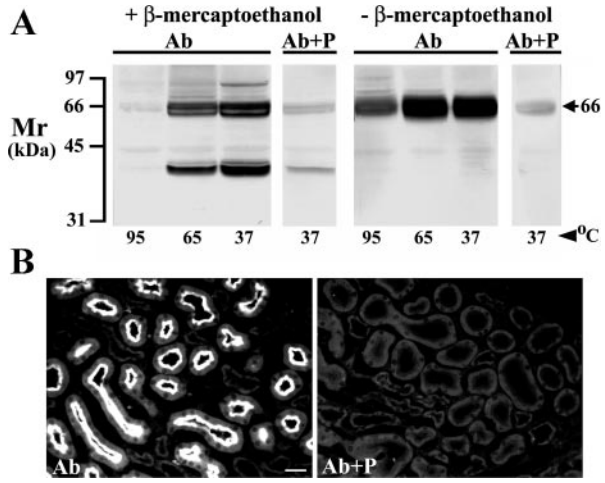

Fig. 2. Testing of rOAT2-Ab specificity by immunoblotting (*A*) and immunocytochemistry (*B*) in the samples from rat kidney. *A*: total cell membranes, isolated from the F kidney outer stripe homogenate, were prepared in reducing (+β-mercaptoethanol) or nonreducing (−β-mercaptoethanol) conditions at the indicated heating temperatures for 5 min (95°C), 15 min (65°C), or 30 min (37°C) and blotted with the rOAT2-Ab (Ab) or with the antibody that had been preincubated with the immunizing peptide (Ab+P). Two major protein bands (~40 and ~66 kDa) were labeled in reducing conditions, whereas only one band (~66 kDa) was labeled in nonreducing conditions. In both conditions, the bands increased with decreasing temperature and were largely blocked by the peptide. Each lane contained 60 μg of protein. *B*: by immunocytochemistry, brush border of the proximal tubule S3 segment in the outer stripe was strongly stained (Ab), and this staining was blocked by the immunizing peptide (Ab+P).

which caused an upregulation of rOAT2 (Fig. 1*B*). The expression of β-actin mRNA was unchanged in all experimental conditions. Similar, but more heterogeneous, data were observed for mRNA expression in the renal cortical tissue from the same animals (data not shown).

Specificity of rOAT2-Ab in immunoblotting and immunocytochemical studies with the samples from rat kidney. Before detailed immunolocalization of the rOAT2 protein in rat kidney was performed, the rOAT2-Ab specificity was tested by immunoblotting TCM preparations from the F kidney outer stripe homogenate and by immunostaining cryosections of the same tissue. Different experimental conditions were applied, without or with inactivation of the rOAT2-Ab with the immunizing peptide. As shown in Fig. 2*A*, in reducing conditions, the antibody consistently labeled two protein bands, at ~40 kDa and ~66 kDa, that were strongest after heating at 37°C for 30 min (Ab) and largely diminished after blocking the antibody with the immunizing peptide (Ab+P). In nonreducing conditions, however, only one prominent and consistent peptide-blockable band was labeled, at ~66 kDa, that exhibited similar density after heating at 65°C for 15 min or 37°C for 30 min. A single 66-kDa protein band in nonreducing conditions was clearly stronger than the 66- and 40-kDa bands in reducing conditions, suggesting the reducing conditions as possibly favorable for splitting the 66-kDa holoprotein in two (or more) fragments, one that retained the antibody-binding epitope (40-kDa protein band) and one or more without it (not labeled on the blot). In addition, a weak ~95-kDa band was inconsistently labeled in various blots that was blocked by the immunizing peptide (Fig. 2*A*) but exhibited no clear relevance to blotting

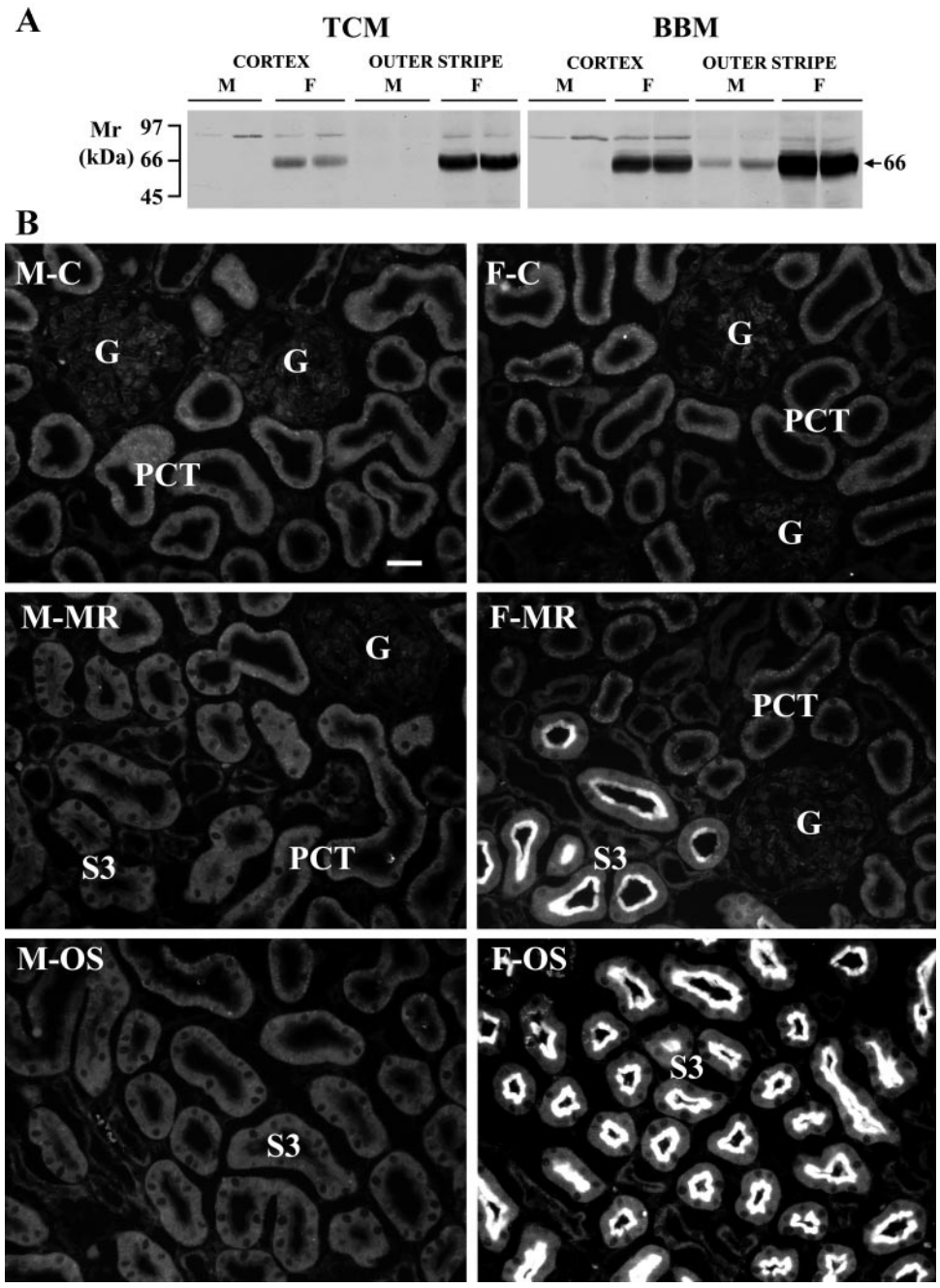

Fig. 3. Zonal and gender differences in the expression of rOAT2 protein in isolated membranes from the cortical and outer stripe tissues (*A*) and in cryosections of the same tissues from the rat kidney (*B*). *A*: comparison of the 66-kDa band in total cell membranes (TCM) and brush-border membranes (BBM) isolated from the cortex (C) and outer stripe (OS). In the membranes from M kidney, the 66-kDa band was either negative or weakly labeled (OS > C), whereas in the membranes from F kidney, the band was labeled in both zones, being much stronger in the OS. Blots were performed with 60 μg (TCM) and 30 μg (BBM) protein/lane. *B*: no significant immunostaining was observed in cryosections of the M kidney superficial cortex (M-C), medullary rays (M-MR), and outer stripe (M-OS), whereas in the F kidney, tubules in the superficial cortex were negative (F-C), but the brush border of proximal tubule S3 segment (S3) in medullary rays (F-MR) and outer stripe (F-OS) was brightly stained. Glomeruli (G) and proximal convoluted tubules (PCT) were negative. Bar = 20 μm.

conditions (Fig. 2*A*), gender (Fig. 3*A*), gonadectomy (Fig. 4*A*), or hormonal treatment (Fig. 6*A*), thus reflecting an OAT2-irrelevant protein that was present in membrane preparations as a variable contamination and was, therefore, neglected. In tissue cryosections, using the optimal experimental conditions and the steps of antigen retrieval, the antibody strongly stained the brush border of proximal tubule S3 segments in the F rat kidney (Fig. 2*B*, Ab). This staining was completely blocked by the immunizing peptide (Fig. 2*B*, Ab+P). In further immunoblotting studies, the membranes were prepared in nonreducing conditions at 37°C for 30 min, whereas the antigen retrieval technique was applied to screen localization of OAT2 in tissue cryosections.

Zonal and gender differences in the expression of OAT2 protein in rat kidney. As shown in Fig. 3*A*, TCM from the M kidney cortex exhibited no significant 66-kDa band, whereas in BBM, the band was either negative (cortex) or weak (outer stripe). No significant band was observed in TCM from the inner stripe and inner medulla (data not shown). Accordingly, in cryosections of the M kidney, either no significant staining with the rOAT2-Ab was observed in any of the structures in the cortex and outer stripe (Fig. 3*B*) or a weak brush-border staining was present in the occasional S3 segments in the outer stripe in some sections (c.f. Fig. 4*C*). However, in TCM and BBM from the F kidney cortex and outer stripe, the 66-kDa band was clearly labeled, showing strong zonal differences

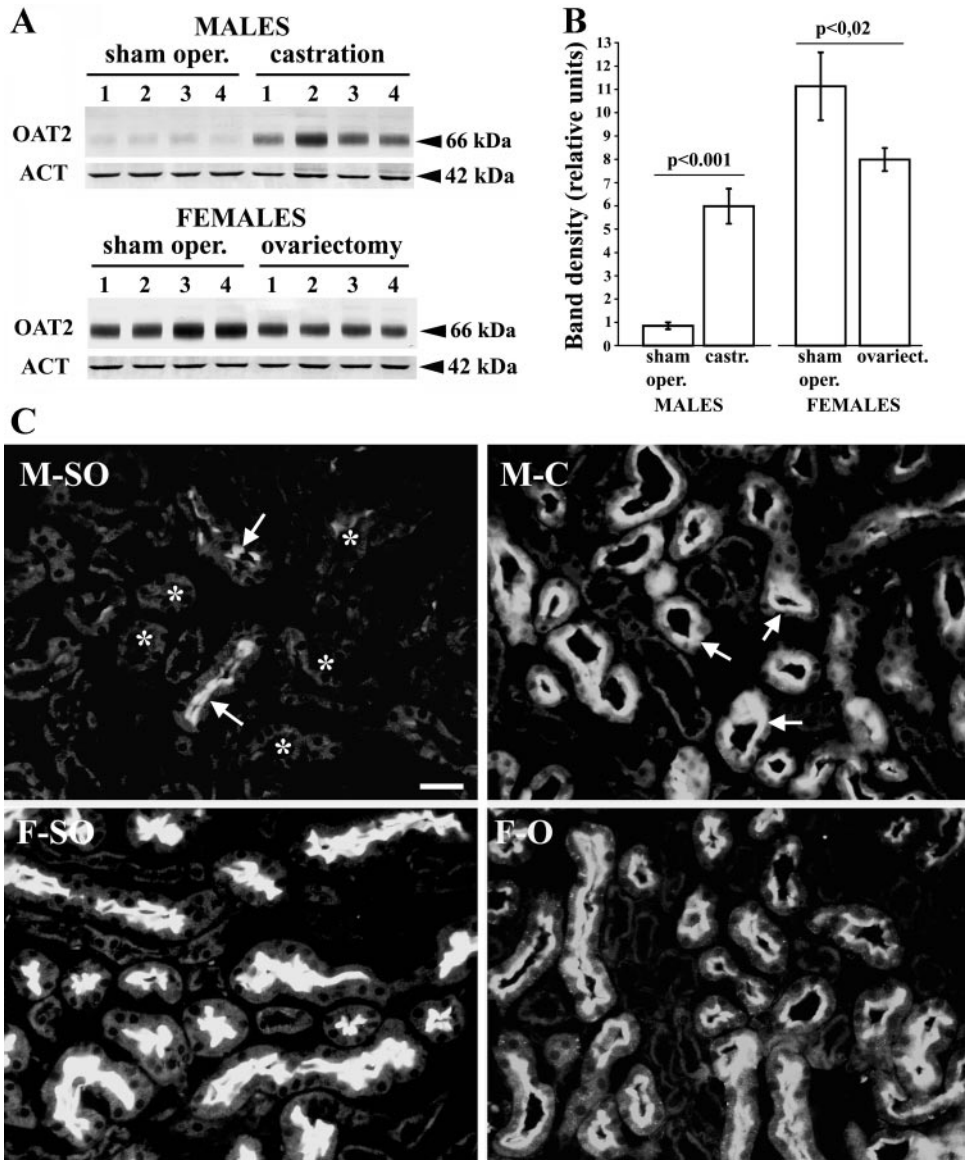

Fig. 4. Effect of castration and ovariectomy on the expression of OAT2 (*A* and *B*) and α-actin (*A*; ACT) in total cell membranes isolated from the outer stripe and OAT2 in cryosections of the same zone of the rat kidney (*C*). *A*: in M rats, the membranes from castrated animals exhibited a much stronger 66-kDa band compared with sham-operated controls, whereas in F rats, the band was weaker in ovariectomized animals compared with controls. The 42-kDa band of α-actin was similar in all the membrane preparations and remained unaffected by gonadectomy. Each band represents membranes from a separate animal. Each lane contained 80 μg of protein. *B*: densitometric evaluation (mean ± SE; $n = 4$ for each experimental group) of the 66-kDa bands shown by immunoblots in *A*. The castrated M exhibited an ~6-fold increase in band density, and the sham-operated F had ~11-fold stronger band density compared with the sham-operated M, whereas the ovariectomized F had ~28% lower band density compared with the respective sham-operated F. *C*: immunostaining of rOAT2 in the inner stripe of sham-operated and gonadectomized rats. In sham-operated M (M-SO), most of the S3 segments were negative (asterisks), and the occasional tubules were weakly apically positive (arrows), whereas the brush border of castrated animals (M-C) was stained much stronger. In sham-operated F (F-SO), the brush border of all S3 segments was brightly stained; the staining intensity was weaker in ovariectomized animals (F-O). Bar = 20 μm.

(outer stripe > cortex) (Fig. 3*A*). The band was absent in TCM from the inner stripe and inner medulla (data not shown). By immunocytochemistry, the staining in F kidney was negative in the superficial cortex, whereas the brush border of S3 segments in the medullary rays and outer stripe was brightly stained (Fig. 3*B*). No significant staining was observed in the inner stripe and inner medulla of M and F kidneys (data not shown). This experiment, therefore, indicates gender (F > M) and zonal (outer stripe > cortex) differences in the expression of OAT2 protein in rat kidney due to an exclusive presence of this transporter in the brush border of proximal tubule S3 segments.

To determine the sex hormone(s) responsible for the observed zonal and gender differences in the expression of OAT2 protein in rat kidney, animals from both sexes were gonadectomized, and castrated M were treated with various sex hormones before immunoblotting and immunocytochemical studies. Because of the exclusive localization of OAT2 in S3 segments, the following data are shown only for isolated membranes and the tissues from the outer stripe.

Effect of castration and ovariectomy in rats. As shown in Fig. 4, *A* and *B*, 6 wk following castration, the OAT2-related 66-kDa band in the renal outer stripe TCM from castrated rats exhibited an approximately sixfold increase above that in sham-operated M. The band density in sham-operated F was ~11-fold stronger than in sham-operated M and decreased by ~28% following ovariectomy. The immunostaining of brush border in S3 segments was *1*) weak in sham-operated M, *2*) strongly upregulated in castrated M, *3*) strong in sham-operated F, and *4*) partially downregulated in ovariectomized F (Fig. 4*C*). The 42-kDa α-actin band was tested in the same membranes (Fig. 4*A*, ACT) and showed no visible differences in variously treated animals, indicating similar protein loading and comparable transfer efficiency. This experiment thus indicates that the expression of OAT2 protein in the rat kidney S3 segments is controlled by inhibitory actions of androgens and stimulatory actions of the F sex hormones.

Expression of OAT2 protein in prepubertal rats. The expression of OAT2 protein in the outer stripe was tested in 20- to

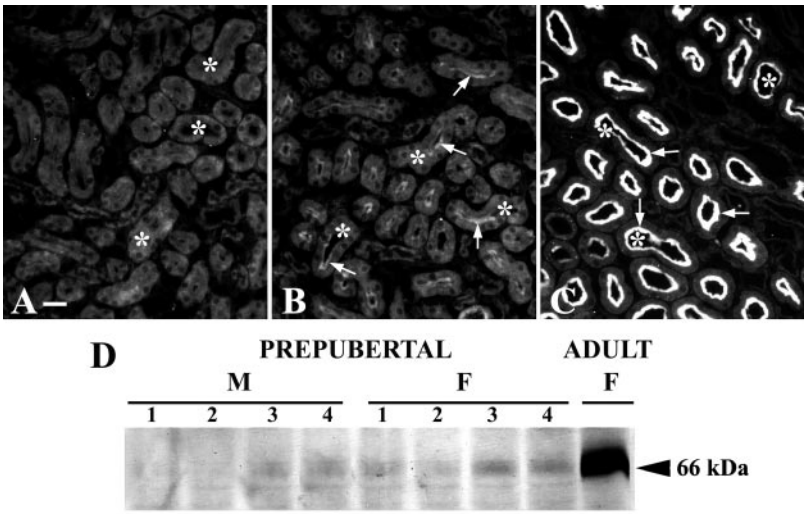

Fig. 5. Expression of rOAT2 protein in the kidney outer stripe of prepubertal rats. *A–C*: immunostaining in the renal outer stripe. In prepubertal rats, the brush-border staining in S3 segments (asterisks) was negative in M (*A*) and very weak in F (*B*, arrows) and comparatively very strong in the adult F (*C*, arrows). Bar = 20 μm. *D*: immunoblotting of rOAT2 in the renal outer stripe total cell membranes from prepubertal M (PPM) and F (PPF) and from an adult F (AF). Compared with that in the adult animal, the rOAT2-related protein band was very weak in prepubertal animals of both sexes. Each lane contained 80 μg of protein and represents membranes from a separate animal.

25-day-old rats of both sexes; as shown in Fig. 5, *A* and *B*, no significant staining with rOAT2-Ab in M rats (Fig. 5*A*) and a very weak staining in F rats (Fig. 5*B*) were observed in the brush-border domain of S3 segments. This pattern of protein expression was confirmed by immunoblotting of TCM isolated from the outer stripe tissue (Fig. 5*D*). The experiment shows that the OAT2 protein expression in rat kidney is very low before the onset of puberty, thus indicating that the observed zonal and gender differences in the OAT2 protein expression in adult animals are related to the levels of sex hormones after puberty.

Effect of sex hormone treatment in castrated rats. To determine the sex hormone responsible for zonal and gender differences in OAT2 expression in adult animals, castrated rats were treated with either oil (control) or various sex hormones (Fig. 6). The immunoblotting data in TCM from the outer stripe of variously treated animals (Fig. 6*A*) and densitometric data of the respective 66-kDa band (Fig. 6*B*) showed that testosterone treatment caused a strong decrease of the elevated band density in castrated rats to the levels observed in sham-operated, oil-treated animals, whereas estradiol and progesterone treatment caused a limited additional upregulation of the band density. The 42-kDa α-actin band in the same membranes (Fig. 6*A*) showed no visible differences in variously treated animals, indicating similar protein loading and comparable transfer efficiency. The immunocytochemical data for OAT2 were completely corroborating (Fig. 6*C*); in accordance with the data in Fig. 4, the staining was largely negative in the outer stripe of sham-operated animals and was clearly enhanced in oil-treated castrated rats. However, testosterone treatment strongly diminished, whereas estradiol and progesterone treatment partially enhanced the brush-border staining in S3 segments of castrated rats. This set of experiments thus indicates that androgens downregulate, whereas estrogens and progesterone upregulate, expression of OAT2 protein in the brush border of S3 segments in rats.

Specificity of rOAT2-Ab in immunoblotting and immunocytochemical studies with the samples from mouse kidney. Previous mRNA studies in mice indicated very low expression of mOAT2 in liver and kidney of the fetal and prepubertal animals (8, 39), and possible gender differences in its expression in liver (F > M) but not in kidney (8, 27) of the adult animals. The amino acid sequence of the rOAT2-immunizing peptide, which is common to both rOAT2 and mOAT2, indicated that the rOAT2-Ab could cross-react with mouse tissues. Indeed, as shown by immunoblotting in TCM and BBM isolated from the whole F mouse kidney, the rOAT2-Ab labeled a single peptide-blockable band at 66 kDa (Fig. 7*A*), whereas by immunocytochemistry, the antibody strongly stained the brush-border domain of proximal tubule S3 segments in the F kidney outer stripe (Fig. 7*B*). This staining was blocked after preincubating the antibody with the immunizing peptide (Fig. 7*C*). The experiments indicate that the rOAT2-Ab cross-reacts with the mOAT2 and was further used for testing the localization of OAT2 protein in the mouse kidney.

Zonal and gender differences in the expression of OAT2 protein in mouse kidney. As shown in Fig. 8, *A–D*, zonal and gender differences in the expression of OAT2 protein are visible by immunostaining cryosections of the mouse kidney. In the M mouse kidney, cortical tubules and other structures exhibited no significant staining (Fig. 8*A*), whereas the brush-border of proximal tubule S3 segments in the outer stripe was weakly stained (Fig. 8*C*). In the cortex of F mouse kidney, only the brush border of S3 segments in medullary rays was fragmentary and weakly stained (Fig. 8*B*), whereas the brush border of S3 segments in the outer stripe was brightly stained (Fig. 8*D*). In immunoblots of the whole mouse kidney BBM, the protein bands related to Na-K-ATPase and AQP1 were similar in both sexes (Fig. 8*E*), whereas the mOAT2-related 66-kDa band was much stronger (~10-fold) in membranes from the F kidneys (Fig. 8, *E* and *F*). Therefore, this set of experiments shows that the expression of OAT2 in mouse kidney exhibits zonal (outer stripe > cortex) and gender differences (F > M) similar to those in rat kidney.

DISCUSSION

The data shown in this report, which were obtained with RT-PCR, Western blotting, and immunocytochemistry, revealed a complete congruency in the expression of renal OAT2-specific mRNA and protein in rats, exhibiting *1*) zonal (outer stripe > cortex) and gender (F > M) differences, *2*)

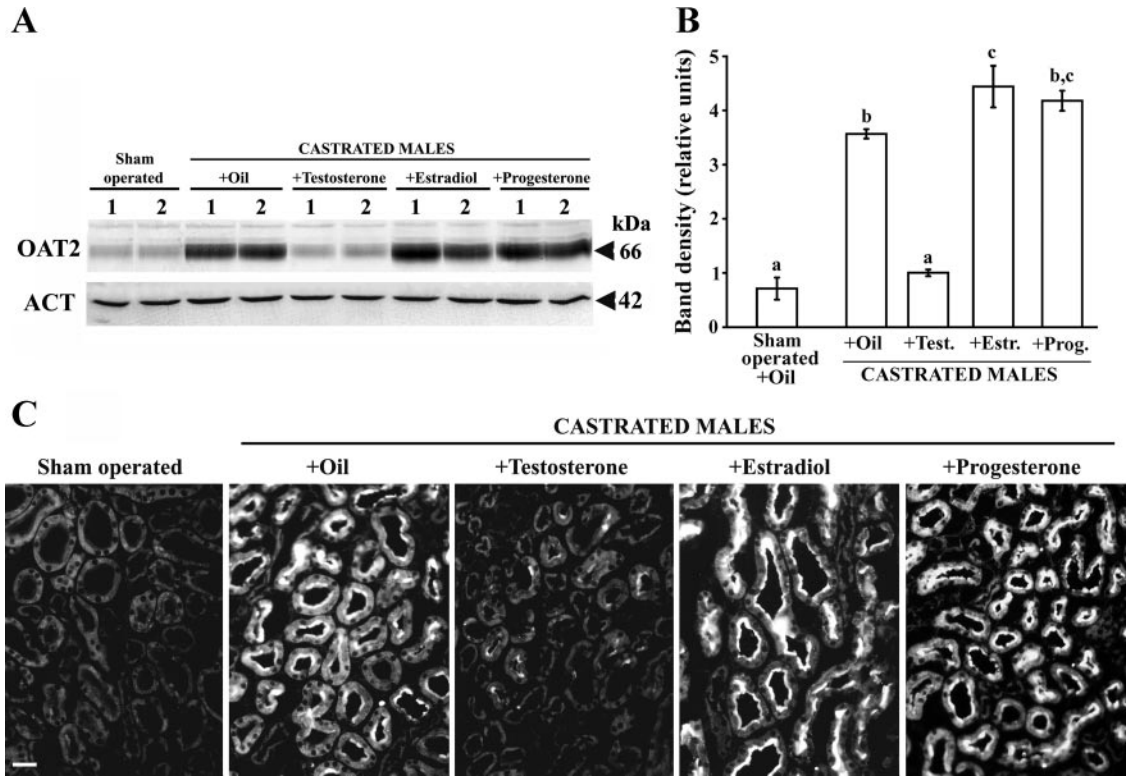

Fig. 6. A representative immunoblot of rOAT2 and α-actin (ACT) with the total cell membranes (each lane contained 80 μg of protein) from the kidney outer stripe (*A*), densitometric evaluation of the rOAT2-related 66-kDa protein band in the blot (*B*), and the respective immunostaining in tissue cryosections (*C*); effect of castration and treatment with various sex hormones in M. *A*: representative blots with membranes from 2 animals in each experimental group. The 42-kDa actin band exhibited no visible differences among various animals, indicating similar loading and transfer. *B*: densitometric data of the 66-kDa band, collected from 2 independent experiments ($n = 4$ in each experimental group); compared with that in sham-operated controls (Sham operated + oil), the density of the 66-kDa protein band was strongly enhanced (~4.5-fold) in castrated rats treated with oil (+Oil); this elevation was downregulated by testosterone treatment to the level of sham-operated animals (+Test), whereas the estradiol (+Estr) or progesterone (+Prog) treatment caused, respectively, an additional significant or limited upregulation vs. oil-treated castrated animals. Statistics: a vs. b or c, $P < 0.001$; b vs. c, $P < 0.05$; other relations, nonsignificant (NS). *C*: immunocytochemically, S3 segments were not stained in the sham-operated + oil-treated rats, BBM of the oil-treated castrated rats was brightly stained, and this staining was strongly diminished after treating animals with testosterone, whereas the staining intensity in estradiol- or progesterone-treated castrated animals was slightly enhanced. Bar = 20 μm.

localization in the brush border of proximal tubule S3 segments (F > M), *3*) weak and gender-independent expression in prepubertal animals, and *4*) similar pattern following gonadectomy and treatment with sex hormones. In addition, the OAT2 protein in mice kidneys exhibited a pattern of localization and gender differences that largely resembled that in rats.

The data of OAT2 mRNA expression in rat kidney, with clear gender differences (F > M), upregulation by castration and downregulation by ovariectomy, as well as downregulation by testosterone and upregulation by estradiol and progesterone treatment in castrated M rats, are in fair agreement with most previously published findings (6, 7, 24, 29). These findings were further corroborated with the immunoblotting data in cell membranes isolated from various kidney zones in rats, showing a comparable gender- and sex hormone-dependent pattern of the rOAT2 protein content. rOAT2 was identified as a temperature- and denaturing condition-sensitive protein exhibiting slightly lower electrophoretic mobility (~66 kDa) than previously observed for the protein in rat liver (52–62 kDa) (36, 50) and kidney (60 kDa) (28). Having 535 amino acid residues (50), the native protein in nonglycosylated state should run to ~59 kDa; the observed location of the band at 66 kDa most probably reflected the glycosylated form of the protein. The pattern of 66-kDa band density in isolated membranes from the renal outer stripe of M, F, and variously treated castrated M rats completely matched the pattern of mRNA expression in the same tissue. Moreover, our immunocytochemical studies revealed *1*) localization of the protein exclusively in the brush border of proximal tubule S3 segments that reside in the outer stripe and in medullary rays and *2*) a pattern of the staining intensity of the brush border in S3 segments comparable to that of mRNA expression and the 66-kDa band density. Taken together, our data showed a missing correlation of the renal OAT2 expression at the levels of mRNA and protein and revealed BBM of the proximal tubule S3 segment as the principal localization of the OAT2 protein in the rat nephron, which is different from the previously attributed localization to the apical membrane of TALH and cortical and medullary collecting ducts in the rat kidney (28). Furthermore, finding of the weak and gender-independent expression of the renal OAT2 protein in prepubertal rats is completely in agreement with previous data showing low mRNA expression in rats under the age of 35 days (6, 50).

In mice, previous studies of the renal OAT2 mRNA indicated its low expression in fetal and prepubertal age and absence of gender differences in adult animals (8, 27, 39). In

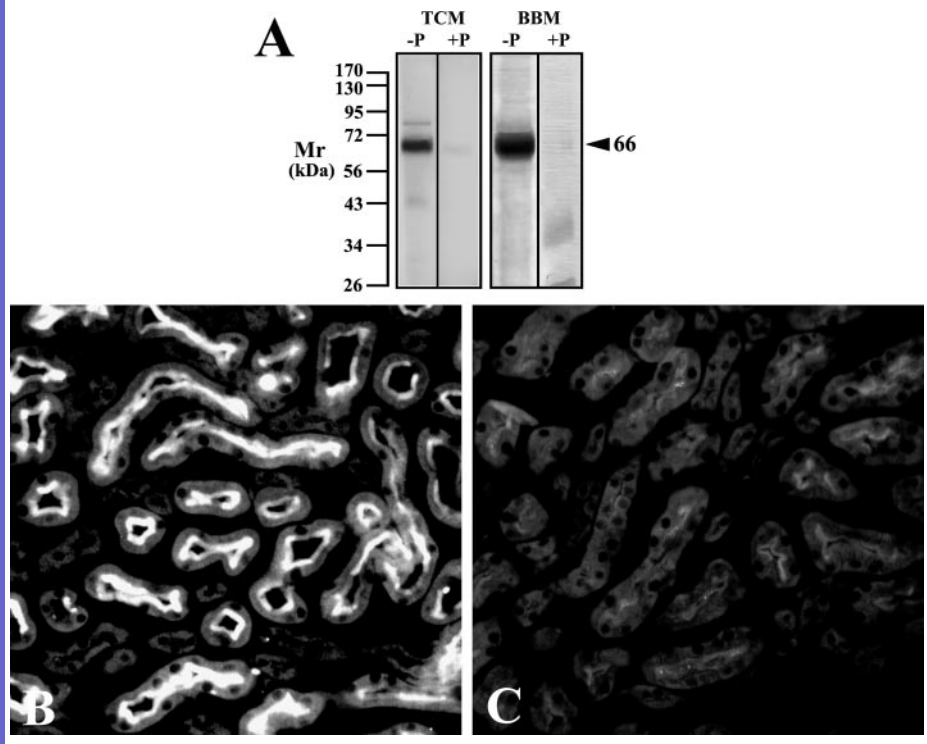

Fig. 7. Testing of rOAT2-Ab specificity by immunoblotting (*A*) and immunocytochemistry (*B* and *C*) in the samples from mouse kidney. *A*: TCM (60 μg protein/lane) and BBM (30 μg protein/lane), isolated from the total F kidney homogenate, were prepared in nonreducing conditions (heating for 15 min at 65°C) and blotted with the rOAT2-Ab (−P) or with the antibody that had been preincubated with the immunizing peptide (+P). In both cases, only 1 significant band of ~66 kDa was labeled that was completely blocked by the peptide. By immunocytochemistry, the brush border of proximal tubule S3 segments in the outer stripe was brightly stained (*B*), and this staining was largely blocked by the immunizing peptide (*C*).

paraffin sections of the M mouse kidney, mOAT2 was recently localized to the luminal membrane of proximal tubules (the segments were not identified) (25). Our data showed that the pattern of localization and gender-dependent expression of OAT2 protein in the mouse proximal tubule S3 segments is basically similar to that in rats, except the staining in M mice was always weakly positive as opposed to the relevant staining in M rats, which was largely negative, whereas the staining in F was strong in both species. The reason for a discrepancy in the expression of renal OAT2 mRNA and protein in mice is unknown and indicates possible sex hormone-dependent post-transcriptional regulation of the OAT2 protein expression in mice, whereas in rats, this regulation seems to be principally transcriptional.

Contrary to the localization of OAT2 in the brush border of S3 segments in rats and mice, the transporter in the human kidney (hOAT2) was immunolocalized to the basolateral membrane of cortical proximal convoluted tubules (13), but possible gender differences in its mRNA and/or protein expression/localization have not been reported. The hOAT2 isoforms (hOAT2A and hOAT2B) are slightly longer than rOAT2 at the COOH-terminal domain, having 546 (hOAT2A) and 538 (hOAT2B) amino acid residues; the isoform hOAT2A exhibits 79% homology to rOAT2 (51). It is unknown whether different COOH-terminal domains represent any discriminating factor for completely different intracellular segregation and targeting of OAT2 to the brush-border (rOAT2 and mOAT2) or basolateral (hOAT2) membrane domains.

The (patho)physiological and possible toxicological implications of the exclusive OAT2 localization in the BBM of S3 segments and its much stronger expression in F rats and mice, as demonstrated in this study, are not clear. Information on the substrate specificity of OAT2 in the mammalian liver and kidney is limited and indicates some differences and similarities among species when studied in the in vitro expression systems: rOAT2 does, but hOAT2 and mOAT2 do not, transport salicylate (27, 48, 51), whereas both rOAT2 and hOAT2 transport some prostaglandins, cephalosporin antibiotics, and other chemotherapeutics (13, 22, 36). Much less is known on the role and substrate specificity of OAT2 in the kidney of experimental animals and humans in vivo, particularly with respect to localization of the transporter in the opposite cell membrane domains. Because of unknown driving forces and nonselective substrate specificity, it is also hard to define a role(s) of the apical and basolateral OAT2 in reabsorptive and/or secretory processes.

The sex-related differences in pharmacokinetics and pharmacodynamics of various exogenous drugs and toxic substances have been documented in animal and human kidney, liver, intestine, and brains (reviewed in Refs. 15, 17, 33, 35, 37). In human and veterinary medicine, these differences may affect the rate of reabsorption, secretion, and therapeutic efficiency and cause adverse reactions to and organotoxicity of various drugs. Numerous information has been collected over the past decade indicating various specific membrane-bound transporters of OA and cations as the critical players in these processes (reviewed in Refs. 4, 12, 14, 18, 19, 31, 35, 37, 38, 40, 52, 53–57). One classic example is the well-studied excretion of PAH in the rat kidney, which is strongly gender dependent (M > F) (3, 23, 41) because of corresponding gender differences in the expression of PAH transporters OAT1 (Slc22a6) and OAT3 (Slc22a8) in the proximal tubule basolateral membrane (M > F) that are caused by androgen stimulation and estrogen inhibition (32). A number of other diagnostic and therapeutic and other potentially toxic but structurally unrelated organic substances have been described whose renal clearance (urine excretion) in rats was gender related, such as aldose reductase inhibitor zenarestat, tauro-

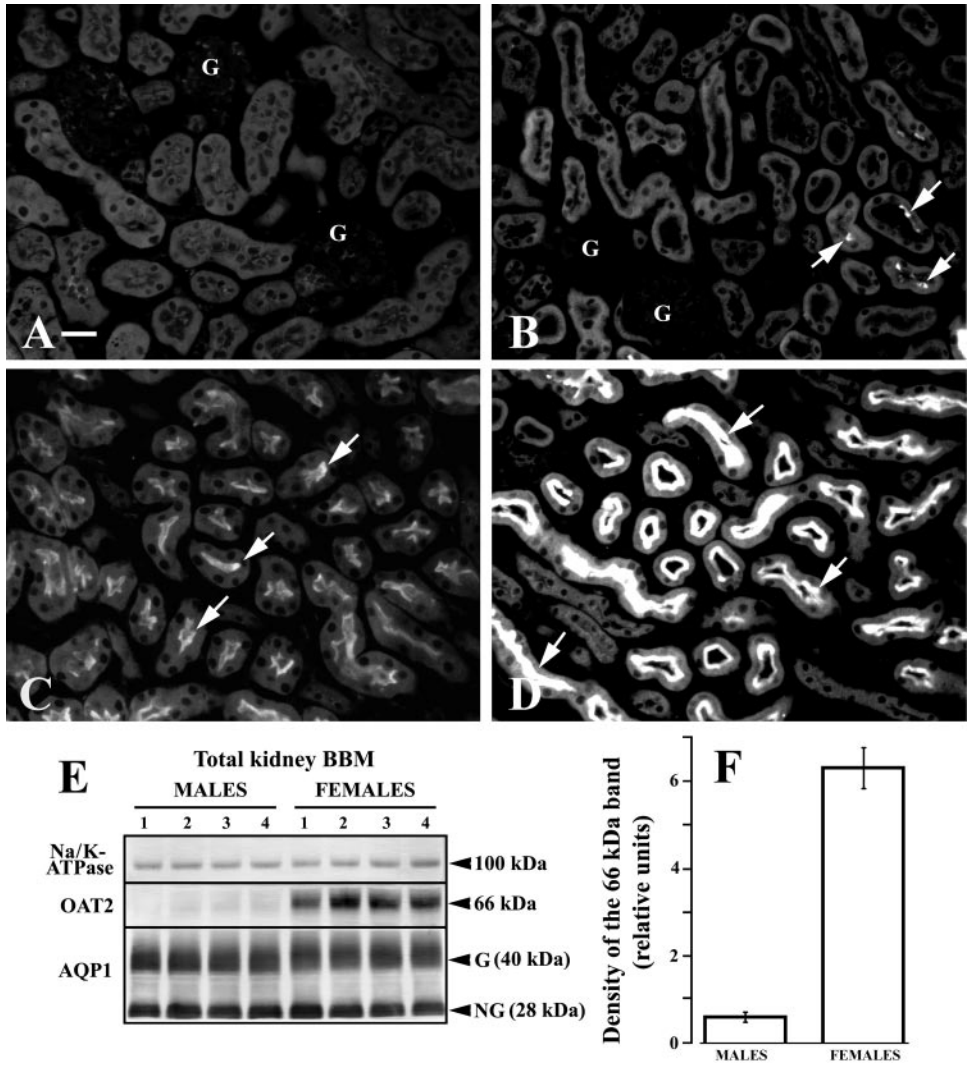

Fig. 8. Zonal and gender differences in the expression of OAT2 protein in cryosections of the mouse kidney (*A–D*), the abundance of Na-K-ATPase, OAT2 and aquaporin-1 (AQP1) in BBM isolated from the whole mouse kidney homogenates (*E*), and densitometric evaluation of the OAT2-related 66-kDa protein (*F*). By immunocytochemistry, in the M kidney, none of the tubule profile was stained in the cortex (*A*), whereas brush border of the proximal tubule S3 segments in the outer stripe was weakly stained (*C*, arrows). In the F kidney, most of the tubules in the cortex were not stained, except for S3 segments in the medullary rays, whose brush border was fragmentary and weakly stained (*B*, arrows), whereas brush border of the S3 segments in the outer stripe was strongly stained (*D*, arrows). G, glomeruli. Bar = 20 μm. In immunoblots of the total kidney BBM (*E*), the abundances of Na-K-ATPase (~100-kDa band of the α-subunit) and AQP1 (nonglycosylated 28-kDa and glycosylated ~40-kDa bands) were similar in membrane preparations from both sexes, indicating similar quality of isolated membranes, whereas the OAT2-related 66-kDa band was much stronger in membranes from the F kidneys. Each lane contained 30 μg of protein. Densitometric evaluation of the 66-kDa band (*F*) exhibited ~10-fold higher abundance of this protein in F animals (n = 4 in each experimental group, $P < 0.001$).

cholate and dibromosulfophtalein (F > M) (21, 54), estradiol-17β-glucuronide (F > M) (16), anti-ulcer drug egualen sodium (F > M) (45), semisynthetic penicillin metabolite cyclacillin (F > M) (20), and 2-butoxyethanol (M > F) (11). Whereas gender-dependent excretion of zenarestat, taurocholate, and dibromosulfophtalein may be related to the renal expression of OA-transporting polypeptide-1 (OATP1/Slc21a1) in the brush border of proximal tubule S3 segments, which is stimulated by androgens at both the mRNA and protein levels (34) and thus may mediate much higher reabsorption of these substrates in M rats (21, 16), gender differences in the excretion of other above-mentioned substances have not been correlated to any specific transporter so far.

As a transporter for cyclosporin antibiotics, OAT2 may contribute to a well-known nephrotoxicity by these compounds in humans (22), but information regarding possible gender differences of the hOAT2 in the proximal tubule basolateral membrane and nephrotoxicity are not available. On the other side, sex hormone-driven gender differences in the expression of rOAT2 protein in the brush border of proximal tubule S3 segments in rats (this study) are in fair correlation with the OAT2 mRNA expression and renal excretion of an occupational toxicant, perfluorooctanoic acid (PFOA), whose clearance is much lower in M rats, increased by castration, and decreased strongly by testosterone and weakly by estradiol treatment in castrated animals (29). This putative correlation, "substrate clearance-rOAT2 expression," implies that the transporter would act in secretory mode and would transport less PFOA in M. However, a number of other OA transporters exist at the basolateral or BBM domains in proximal tubules whose driving forces are only partially or ill defined, with a wide substrate specificity and undefined reabsorptive or secretory mode of action in vivo, and a number of them may exhibit gender differences that could interfere with the PFOA excretion.

In summary, our study indicates that the rat renal OAT2 is localized exclusively in the brush border of proximal tubule S3 segments, causing zonal (outer stripe > cortex) and gender differences (F > M) in both mRNA and protein expression that are determined by androgen inhibition and estrogen and progesterone stimulation, and appear after puberty. A similar gender-dependent pattern of OAT2 expression also exists in the mouse kidney. The impact of these findings on gender- and age-related reabsorption, secretion, and nephrotoxicity of endogenous and exogenous OA in rodents should be defined in future studies. Furthermore, keeping in mind the different

localization of the OAT2 protein in rodents (BBM of the proximal tubule S3 segment) and humans (basolateral membrane of the proximal tubules), it is unclear whether rodents can serve as a plausible model for humans with regard to the proposed role of OAT2 in renal physiology and nephrotoxicity, so that further experimentation is urged to resolve species differences in the OAT2 expression and function(s).

ACKNOWLEDGMENTS

We thank the company Transgenic, Incorporated (Kumamoto, Japan), for providing the anti-rOAT2 antibody and Mrs. Eva Heršak for expert technical assistance.

GRANTS

This work was supported by Grant no. 0022011 (I. Sabolić) from the Ministry for Science, Education and Sports, Republic of Croatia.

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