A primary culture of mouse proximal tubular cells, established on collagen-coated membranes

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1Laboratory of Cell Physiology and 2Laboratory of Histology, Hasselt University and Transnationale Universiteit Limburg, 3Biomedical Institute and 4Centre for Environmental Sciences, Diepenbeek, Belgium; and 5Division of Nephrology, Université Catholique de Louvain, Brussels, Belgium

Submitted 11 September 2006; accepted in final form 28 April 2007

Terry S, Jouret F, Vandenabeele F, Smolders I, Moreels M, Devuyst O, Steels P, Van Kerkhove E. A primary culture of mouse proximal tubular cells, established on collagen-coated membranes. Am J Physiol Renal Physiol 293: F476–F485, 2007. —A simple method is described to establish primary cultures of kidney proximal tubule cells (PTC) on membranes. The permeable membranes represent a unique culture surface, allowing a high degree of differentiation since both apical and basolateral membranes are accessible for medium. Proximal tubule (PT) segments from collagenase-digested mouse renal cortices were grown for 7 days, by which time cells were organized as a confluent monolayer. Electron microscopic evaluation revealed structurally polarized epithelial cells with numerous microvilli, basolateral invaginations, and apical tight junctions. Immunoblotting for markers of distinct parts of the nephron demonstrated that these primary cultures only expressed PT-specific proteins. Moreover, immunodetection of distinct components of the receptor-mediated endocytic pathway and uptake of FITC-albumin indicated that these cells expressed a functional endocytotic apparatus. In addition, primary cultures possessed the PT brush-border enzymes, alkaline phosphatase, and γ-glutamyl-transferase, and a phloridzin-sensitive sodium-dependent glucose transport at their apical side. Electrophysiological measurements show that the primary cultured cells have a low transepithelial resistance and high short-circuit current that was completely carried by Na+ similar to a leaky epithelium like proximal tubule cells. This novel method established well-differentiated PTC cultures.

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Renal cortices were dissected visually in ice-cold dissection solution (DS) (HBSS with in mmol/l: 10 glucose, 5 glycine, 1 alanine, 15 HEPES, pH 7.4 and osmolality 325 mosmol/kgH2O) and sliced into pieces of ~1 mm wide. The fragments were transferred to collagenase solution [DS with 0.1% (wt/vol) type-2 collagenase and 96 µg/ml soybean trypsin inhibitor] at 37°C and digested for 30 min. After digestion, the supernatant was sieved through two nylon sieves (pore size 250 µm and 80 µm). Different sieves with pore sizes ranging from 50 to 110 µm were used. Only the 80-µm sieve yielded a large number of long proximal tubule (PT) fragments (about 100 µm in length) without substantial contamination of other nephron segments or glomeruli. The 50-µm sieve used before in our lab to purify medullary thick ascending limbs (15) was not optimal since it retained too many glomeruli. The longer PT fragments remained in the 80-µm sieve and were resuspended by flushing the sieve in the reverse direction with warm DS (37°C) containing BSA 1% (wt/vol). The PTs present in the BSA solution were centrifuged for 5 min at 170 g, washed, and then resuspended into the appropriate amount of culture medium: 1:1 DMEM/F12 without phenol red and supplemented with heat-inactivated FCS 1%, HEPES 15 mmol/l, L-glutamine 2 mmol/l, hydrocortisone 50 nmol/l, insulin 5 µg/ml, transferrin 5 µg/ml, selenium 50 nmol/l, sodium pyruvate 0.55 mmol/l, 100X nonessential amino acids 10 ml/l, penicillin 100 IU/ml and streptomycin 100 µg/ml buffered to pH 7.4 and osmolality of 325 mosmol/kgH2O. The PT fragments were seeded onto collagen-coated permeable PTFE-filter supports and left unstirred for 48 h at 37°C and 95% air-5% CO2 in a humidified, 5% CO2 in air incubator. After 7 days, cell cultures were organized as a confluent monolayer. PTC were also grown on plastic Thermanox supports and left unstirred for 48 h at 37°C and 95% air-5% CO2 in a humidified, 5% CO2 in air incubator. The longer PT fragments remained in the 80-µm sieve. The supernatant was discarded, and the pellet was washed with PBS. After another centrifugation, the pellet was snap-frozen in liquid nitrogen and stored at ~80°C until further use. Frozen pellets were solubilized in ice-cold lysis buffer containing protease inhibitors (Complete Mini; Roche Diagnostics, Leuven, Belgium), briefly sonicated (Branson Sonifier 250, two pulses at 40% intensity), and then centrifuged at 16,000 g for 1 min at 4°C. The supernatant was transferred into tubes containing 10% SDS and heated at 95°C for 90 s. Protein extracts were separated by SDS-polyacrylamide gels and transferred to nitrocellulose. After blocking, membranes were incubated overnight at 4°C with the first antibody, washed, incubated with peroxidase-labeled secondary antibody, and visualized with enhanced chemiluminescence. For reprobing, the membranes were rinsed, incubated for 30 min at 55°C in a stripping buffer (62.5 mmol/l Tris-HCl, 2% SDS, 100 mmol/l mercaptoethanol, pH 7.4), before incubation with primary antibodies. The signal obtained on membrane extracts from an adult C57/BL6 mouse kidney was expected to have a low alkaline phosphatase activity. Immunostaining. After permeabilizing with Triton, 7-day-old confluent monolayers of primary cultured PTC were incubated with 3% BSA for 1 h before adding the primary antibody diluted in PBS that contained 3% BSA. After washing in PBS, cultures were incubated successively with biotinylated secondary anti-IgG antibodies, avidin-biotin peroxidase and aminoethylcarbazole or diaminobenzidine (Vector Laboratories, Burlingame, CA). Sections were viewed under a Nikon Eclipse 80i (Nikon, Tokyo, Japan). The specificity of immunostaining was tested by incubation in the absence of primary antibody. The quality of the immunostaining is not optimal due to interference of the filter, which can be observed by the striped aspect on the image. Furthermore, the filter is not flat but a wavy surface, and therefore it is difficult to obtain a good focus of all cells of the monolayer. These aspects make these filters less suited for histological purposes compared with glass coverslips or Thermannox.

Antibodies. Immunoblotting and immunostaining analyses were performed using well-characterized sheep polyclonal antibodies against megalin (a gift from P. Verroust, Paris, France) (7); rabbit affinity-purified polyclonal antibodies raised against the NH2 terminus of the human CIC-5 (33); NaCl cotransporter (NCC; a gift from J. Loffing, Lausanne, Switzerland) (18); AQP1 (Chemicon, Temecula, CA); AQP2 (Alomone Labs, Jerusalem, Israel); and sodium-dependent glucose cotransporter type 1 (SGLT1; Abcam, Cambridge, UK) and SGLT2 (Gentaur, Brussels, Belgium); mouse monoclonal antibodies against the 31 kDa E1-subunit (V1 domain) of the V-ATPase (a gift from Dr. S. Gluck, University of California, San Francisco, CA) (5); and β-actin (Sigma, St. Louis, MO).

Uptake of albumin. Uptake of albumin was assessed as described previously (25). Primary PTC were incubated with FITC-labeled bovine serum albumin in Ringer solution for 15 min at 37°C or 4°C as indicated. After rinsing with ice-cold Ringer’s solution, cells were disintegrated with Triton X-100 (0.1% vol/vol in Ringer solution). Intracellular fluorescence was measured using a single-beam fluorimeter (Photon Technology International, Lawrenceville, NY), at an excitation wavelength of 480 nm and emission wavelength at 520 nm. Protein concentration was determined by the Bradford protein assay (4).

Alkaline phosphatase assay and γ-glutamyl-transferase assay. The expression of the PT brush border enzyme, alkaline phosphatase, was assessed spectrophotometrically by the two-point method of Walter and Schütt (32). Enzyme activity was standardized to protein concentrations in the cultures or in freshly isolated proximal tubules (isolated PT) measured by the Bradford protein assay (4). Values obtained from 7-day-old cultures were compared with those of 14-day-old cultures and isolated PT, which resemble more closely the in vivo situation since they retain their tubular morphology. To test the adequacy of the method, Madin-Darby canine kidney (MDCK) cells were used as a negative control. MDCK cells are an established cell line derived from distal tubule or cortical collecting duct from the dog and are therefore expected to have a low alkaline phosphatase activity.

In 7-day-old confluent primary cell cultures and isolated PT, the expression of the brush-border enzyme, γ-glutamyl transferase, was assessed by the method described by Glossmann et al. (13). Cell cultures and isolated PT were incubated with γ-glutamyl-p-nitroanilide in the presence of MgCl2 and glycyglycine in Tris-buffer (0.05M), and the release of γ-glutamyl-p-nitroanilide was measured spectrophotometrically. Enzyme activity was normalized to protein concentrations in the cultures or isolated PT, as measured by the Bradford protein assay (4). One unit of γ-glutamyl-transferase (γ-GT) activity was defined as the amount of enzyme that released 1 µmol of p-nitroaniline per unit time at 37°C.

Assessment of Na⁺-dependent glucose transport. [14C]-α-methyl-D-glucopyranoside (α-MG), a nonmetabolizable glucose analog, was used to study Na⁺-glucose cotransport in primary PT cells. Seven-day-old confluent cultures were washed 3 times with standard transport buffer (containing in mM: 137 NaCl, 5.4 KCl, 1.2 MgSO4, 2.5 CaCl2, 10 HEPES, and 4.0 l-glutamine buffered to pH 7.4 with
Tris-base and osmolality of 325 mosmol/kgH2O with mannitol). To initiate uptake, transport buffer, containing 20 μCi/ml [14C]α-MG, was added at the apical side of the culture. At the basolateral side, standard transport buffer without tracer was added. After the appropriate time of incubation (5, 30, or 60 min), the uptake was stopped by aspirating the apical solution, and the cells were washed rapidly with ice-cold stop solution (standard transport buffer containing 200 μM phloridzin at 4°C). After the final wash, cells were solubilized with 0.1 N NaOH, and aliquots were sampled for liquid scintillation counting and total protein determination (Bradford protein assay; Ref. 4). To assess the Na+-dependence of the transport, NaCl was replaced with choline chloride (137 mM) in the standard transport buffer. Phloridzin sensitivity was determined by adding 200 μM of phloridzin to the apical transport buffer containing NaCl, while standard transport buffer without phloridzin was added to the basolateral side. To test cell polarity, a radioactive tracer was also added at the basolateral side, and uptake was assessed. All uptake studies were performed at 37°C. Values were expressed in picomoles of α-MG taken up per milligram of proteins.

**Measurement of short-circuit current, transepithelial conductance, and capacitance in an Ussing chamber.** To perform electrophysiological measurements, we mounted 7-day-old confluent primary cultures grown on permeable filters in a home-built Ussing-type chamber and short-circuited using a high-speed voltage-clamp technique, according to the method described by Van Driessche et al. (30). During the measurements, cultures were constantly perfused at both sides with warm (37°C) Ringer solution (containing in mM: 138 NaCl, 5.33 KCl, 0.41 MgSO4, 1.26 CaCl2, 0.44 KH2PO4, 0.5 MgCl2, 24 HCO3, 10 HEPES, 4 t-glutamine, 5 glycine, 1 alanine, 5.6 D-glucose at pH 7.4 and 325 mosmol/kgH2O) and continuously bubbled with 1% CO2 and 99% air. In Na+-free Ringer, Na+ was replaced with equimolar concentrations of N-methyl-D-glucamine (NMDG), while in glucose-free Ringer, glucose was replaced with the same concentration of sucrose. Both the apical and basolateral solutions were changed to

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**Fig. 1.** Morphologic characteristics of primary proximal tubule cells (PTC) on polytetrafluoroethylene (PTFE) filter. **A:** LM image showing a confluent monolayer of cells at day 7. **B:** transmission electron microscopy (TEM) image of cobblestone-like cells grown on a collagen-coated filter (Filter). Scale bar: 10 μm. **C:** TEM image showing the presence of apical microvilli (MV), numerous mitochondria (M), and apical tight junctions (TJ). Scale bar: 2,000 nm. **D:** detail of TEM image showing a vacuole (V) associated with the apical membrane and a tight junction (TJ). Also the basolateral infolds (BI) are clearly visible. Scale bar: 1,000 nm. **E:** TEM image of a primary cilium (PC) at the apical membrane and the nucleus (N) with heterochromatin. Scale bar: 1,000 nm. **G:** detail of a basolateral invagination (BI). Scale bar: 500 nm.
prevent backleak of Na\(^+\) or glucose into the apical compartment. For both Ringer solutions, pH and osmolality were kept similar as control Ringer solution at pH 7.4 and 325 mosmol/kg\(\text{H}_2\text{O}\).

Data. All values are expressed as means ± SE. Data from control experiments were fitted with Origin 6.0 (Micoral Software, Northampton, MA) using the best-fit function. For the albumin uptake experiments, data were fitted according to the Michaelis-Menten kinetics. Significance of differences between two means was calculated using the GraphPad InStat software (demo version, GraphPad Software, San Diego, CA). For the alkaline phosphatase and \(\gamma\)-glutamyl transferase experiments, significance was calculated with one-way ANOVA with Bonferroni correction. For the glucose uptake experiments, significance was calculated by the Kruskal-Wallis test (nonparametric ANOVA) with the Dunn’s multiple comparison test. Significance level of the differences of the means is indicated in the legend of each figure.

RESULTS

Primary cell culture. Each cell culture was initiated from the isolation of PT fragments from two kidneys (one mouse). The amount of collected tubules was usually sufficient for 12 collagen-coated PTFE-filter supports. First, PT fragments were left unstirred for 48 h. At this time, cellular outgrowth was observed at the open ends of the tubular fragments. After 7 days, islands of cellular outgrowth became progressively larger to form a confluent monolayer of epithelial polygonal cells.

Transmission electron microscopy. At low magnification, the transverse section revealed that single cells grew as a homogeneous monolayer of cells with cobblestone-like appearance on the PTFE filter (Fig. 1, A and B). The cells were structurally polarized: the apical pole, facing the free surface, differed from the basal pole, toward the underlying support layer. We observed that the apex of the cells exhibited numerous short, regularly oriented microvilli (Fig. 1C). The apical cytoplasm possessed clear vacuoles of varying size, some vacuoles being associated with the apical membrane (Fig. 1D). Coated vesicles were regularly found (Fig. 1E). Well-defined tight junctions interconnected the cells at their apical poles (Fig. 1C–E), whereas the basolateral side of the cells showed membrane invaginations (Fig. 1, D and G). Mitochondria were diffusely distributed in the cytosol, as observed in primary cultures of medullary thick ascending limb cells (15). Also, a primary cilium was present at the apical membrane (Fig. 1F).

When PT cells were grown on Thermanox slides, cellular growth was slower compared with the filter supports, since confluency was not reached after 7 days. Furthermore, cells still showed differentiated characteristics like microvilli, but they lost their epithelial organization (data not shown).

Immunoblotting and immunostaining analysis. Well-characterized antibodies against proximal and distal tubule markers were used to establish the state of differentiation of the primary cultures derived from PT segments (Fig. 2). Immunoreactivity for the water channel, AQP1, showed two specific bands, which correspond to the core (≈28 kDa) and the glycosylated (≈35–50 kDa) forms of the protein, in all samples. By contrast, no signal was detected in the same samples for the thiazide-sensitive NCC and for AQP2, established markers of the early distal convoluted tubule and the collecting duct, respectively. To further characterize the PT cells, immunoblotting for major components of the receptor-mediated endocytosis was performed. The renal chloride channel, CIC-5, which plays a key role along the endocytic pathway in PT cells (7), was clearly detected in all samples, as well as its functional partners, the V-ATPase, and the multiligand receptor, megalin. Note that the molecular mass of CIC-5 was slightly higher in cultured PT cells than in the positive control kidney, which might reflect a differential posttranslational processing, e.g., N-glycosylation, of CIC-5 in cultured PT cells (16). Immunoblotting experiments were confirmed by immunostaining on 7-day-old primary PTC (Fig. 3). Almost all cells stained positive for AQP1 (Fig. 3A), CIC-5 (Fig. 3B), and megalin (Fig. 3C), while practically no cells stained for AQP2 (data not shown).

Uptake of albumin. In PTC, albumin is taken up at the apical side by receptor-mediated endocytosis using the multiligand receptors megalin and cubulin (6). The fluorescent probe, FITC-albumin is routinely used to measure receptor-mediated endocytosis and the uptake process is characterized by saturation kinetics. In our cells, uptake of FITC-albumin at 37°C saturates as a function of dose (Fig. 4, •). Because of the large variability in the analysis, the Lineweaver-Burk plot (Fig. 4, inset) for the cell culture sets with lowest uptake data (▴) and highest uptake (●) was assessed. Both experiments, as well as
the mean (■), have the same apparent $K_m$ (intercept with x-axis) but a different $V_{\text{max}}$ (intercept with y-axis) (Table 1). Using the Michaelis-Menten kinetics (Fig. 4) and the Lineweaver-Burk plot (Fig. 4, inset), the mean maximal uptake ($V_{\text{max}}$) was calculated to be $1.5 \pm 0.6 \text{ ng/\mu g protein/15 min}$, and the apparent $K_m$ (concentration for half-maximum uptake) was estimated at $36 \pm 0.9 \text{ mg/l } (n = 12)$. At $4^\circ \text{C}$, the uptake represents the cell-bound fluorescence and should therefore not rise as a function of dose. Indeed, at this low temperature, the uptake process is delayed and does not rise with higher doses (Fig. 4, ○).

Alkaline phosphatase and $\gamma$-glutamyl-transferase assay. Alkaline phosphatase and $\gamma$GT are enzymes expressed at the brush border of PTC. Their activity can be classically assessed by spectrophotometrical methods based on the color conversion of $p$-nitrophenyl phosphate to $p$-nitrophenol in an alkaline solution or $\gamma$-glutamyl-$p$-nitroanilide to the yellowish $p$-nitroaniline, respectively. To localize the enzymes in our cultures, we tested the solution containing $p$-nitrophenyl phosphate or $\gamma$-glutamyl-$p$-nitroanilide at both apical and basolateral sides of the cells. Enzyme activity for the apical side is presented in Fig. 5. Enzyme activity was also assessed at the basolateral...
side, but no activity was measured. For alkaline phosphatase, the activity in 7-day-old primary PTC was about 20 times higher than in 14-day-old primary cultures, indicating the degree of differentiation is dependent on time in culture (Fig. 5, open bars). In isolated PT, enzyme activity was about 4 times lower than in primary PTC. To test whether the two-point method (32) that we used was adequate to evaluate the uptake of [14C]-α-methyl-D-glucopyranoside (α-MG). To localize the transport of glucose, α-MG was tested at both apical and basolateral sides of the cells. When α-MG was added to the basolateral side, we did not observe any uptake into the cells (data not shown). Therefore, we evaluated α-MG uptake under various conditions at the apical side. The addition of unlabeled α-MG to the transport buffer did not affect uptake of labeled α-MG; therefore data presented in Fig. 6 represent uptake of only labeled α-MG. The time course of α-MG uptake was saturable since it slowly reached a maximum transport rate after 60 min (Fig. 6, ■). The addition of phloridzin (200 μM), a competitive inhibitor of glucose reabsorption, resulted in a significant reduction of the α-MG uptake after 30 and 60 min in the presence of Na⁺† (Fig. 6, ▲). The uptake of α-MG was only 12% of control after 60 min in the presence of phloridzin. When Na⁺ was omitted from the transport buffer and replaced by an equal amount of choline, uptake of α-MG without Na⁺ was significantly reduced after 30 and 60 min (Fig. 6, ●). Omission of Na⁺ reduced transport rates. The maximum rate was only 18% of the control after 60 min. Still a small amount of α-MG was taken up under Na⁺-free conditions. Immuno-staining for the SGLT1 and SGLT2 is shown in Fig. 3 (F+G+L+M). Primary cultures of 7-day-old PTC expressed both SGLT1 and SGLT2.

Electrophysiological characteristics of primary cultured PTC. Cell monolayers were allowed to stabilize to a steady-state level before omitting Na⁺ or glucose from the control Ringer solution. Steady-state values for the short-circuit current (Isc), transepithelial conductance (GT) and capacitance (CT) were determined at 26.85 ± 0.21 μA/cm², 14.98 ± 0.03 mS/cm², and 0.81 ± 0.005 μF/cm², respectively (Fig. 7, n = 3). Replacing Na⁺ for NMDG immediately dropped Isc, while a small drop in GT (22%) and CT (3%) was observed (Table 2). When glucose was replaced by sucrose in the Ringer solution, a drop in Isc, GT and CT could be observed, although the reduction was much smaller than after replacement of Na⁺ for NMDG: 10% decrease for Isc, 8% decrease for GT and 1.2% decrease for CT (Table 1).

Table 1. Calculated apparent Km values and Vmax values for uptake of albumin from culture sets with high and with low uptake compared to the mean

<table>
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<tr>
<th>Cell Culture Set</th>
<th>Apparent Km (mM)</th>
<th>Vmax (μg/mg protein/min)</th>
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<tr>
<td>Mean uptake</td>
<td>36.0 ± 9.0 mg/l</td>
<td>1.5 ± 0.6 ng·μg protein⁻¹·0.15 min⁻¹</td>
</tr>
<tr>
<td>Lowest uptake</td>
<td>35 mg/l</td>
<td>0.4 ng·μg protein⁻¹·0.15 min⁻¹</td>
</tr>
<tr>
<td>Highest uptake</td>
<td>38 mg/l</td>
<td>2.5 ng·μg protein⁻¹·0.15 min⁻¹</td>
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Apparent Km values and Vmax values calculated from the Lineweaver-Burk plot from different sets of cell cultures as indicated in Fig. 4. Different culture sets had different Vmax values, but the same apparent Km value, indicating the presence of the same transport system but a variable level of expression of the transport proteins involved.
DISCUSSION

Microdissection of individual nephron segments was used to culture PT cells from mouse kidney. The microdissection technique has the major advantage of providing pure starting material (15). However, the yield is rather low, and it is a time-consuming method exposing the cells to oxidative or mechanical aggression. PT cells have been shown to be very susceptible to membrane damage during the isolation method compared with tubular fragments of a more distal origin (31). Thus, to properly culture PT cells, we need a fast isolation method with a minimum of aggressive manipulations.

The method described here is a combination of careful dissection of the kidney, enzymatic digestion and sieving. This low cost procedure is characterized by a rather high yield, and it enables a rapid isolation of a large number of PT fragments. When brought into culture, cellular outgrowth is observed at the open ends of the tubular fragments within a few days. After 7 days, a monolayer of polygonal PTC is formed. Taub et al. (28) reported the use of hormonally defined serum-free medium to culture differentiated PTC, with restricted outgrowth of fibroblasts or glomeruli. In our hands, the absence of serum caused a restricted growth of the PT cultures, and a concentration of 1% FCS was necessary to obtain confluent cultures within a reasonable time. No fibroblast overgrowth was observed.

Electron microscopic analysis revealed that confluent monolayers grown on collagen-coated membranes had a cobblestone-like appearance and were polarized with tight junctions confined to the apical poles. Coated vesicles were also observed in the PTC and are known to be involved in the endocytic uptake mechanism of reabsorption of low-molecular weight proteins that have been filtered across the glomerulus. Moreover, the cytosol contained numerous mitochondria and also basolateral invaginations were observed, both character-

![Fig. 5. Alkaline phosphatase and γ-glutamyl-transferase activity in primary PTC. Alkaline phosphatase (AP) activity (open bars, left y-axis) measured in 7-day-old, 14-day-old primary cultures of PTC, Madin-Darby canine kidney (MDCK) cells and freshly isolated proximal tubules (isolated PT). Values (means ± SE) are in micromoles per milligram protein per minute: 129.6 ± 26.6, 7.5 ± 3.2, 0.026 ± 0.004, and 33.7 ± 6.6 for 7-day-old PTC (n = 8), 14-days old PTC (n = 4), MDCK cells (n = 8), and isolated PT (n = 16), respectively. Each value is the mean of different determinations (n). Significance was determined by one-way ANOVA with Bonferroni correction and P values are *P < 0.001 and **P < 0.0001. Gamma-glutamyl-transferase (γGT) (hatched bars, right y-axis) activity was measured in 7-day-old primary cultures of PTC (n = 20) and isolated PT (n = 16) and amounted to a value (means ± SE) of 172.5 ± 13.9 mU/mg protein and 82.7 ± 2.9 mU/mg protein, respectively.

![Fig. 6. [14C]-α-methyl-D-glucopyranoside (α-MG) uptake in primary cultures of PTC. The uptake of α-MG reaches a maximum after about 60 min (●). Glucose transport is sensitive to omission of Na⁺ (●) and can be blocked by phloridzin (◆). Values are means ± SE; each value is the mean of five to seven determinations. Significance was analyzed by Kruskal-Wallis test (nonparametric ANOVA) with the Dunn’s multiple comparisons test and P value was *P < 0.05, **P < 0.01, and ***P < 0.001.

![Fig. 7. Electrophysiological characteristics of primary PTC. Time courses for short-circuit current (Isc), transepithelial conductance (Gt), and transepithelial capacitance (Ct) in basal steady-state conditions and after omission of Na⁺ (No Na⁺), and glucose (No glucose). Traces represent a representative experiment out of three different measurements from 7-day-old confluent primary PTC.
istic features of PTC in vivo. We also show that PTC cultured in our conditions show a primary cilium at the apical membrane, which is another indicator of their differentiation (19). These results indicate that PTC when cultured on permeable collagen-coated filter membranes retain a high degree of morphologic differentiation. By contrast, when grown on a solid support, cells were flatter, and the apical tight junctions were less defined. The PTC developed typical ultrastructural characteristics of myofibroblasts, such as stress fibers.

The presence of specific markers, like transporter proteins or brush-border enzymes, was established to characterize these primary cultures (1). In particular, we evaluated the expression of the PT water channel, AQP1, compared with NCC and AQ2p, which are mostly expressed in the early distal tubule and in the collecting duct, respectively. The PTC cultured in our conditions showed a clear immunoreactivity against AQ1p, while no positive signal for AQ2p or NCC was obtained. These results indicate that our primary cell cultures originated from PT cells, without significant contamination of cells from other parts of the nephron. Moreover, we investigated whether specific markers of the endocytic apparatus were present in our primary cultures. The multiligand receptor, megalin, is located at the brush border of PT cells and participates in protein internalizing albumin in proximal tubule cells (6). As all uptake data are normalized for the amount of protein in each sample, we evaluated the transport of glucose at the apical membrane, another specific cellular function of PT cells. PT cells possess an apical membrane a sodium-dependent glucose transport system (9) ensured by the SGLT-protein (35). Using [14C]-α-methyl-D-glucopyranoside (α-MG), a stable glucose analog, we demonstrated that our primary cultures were capable of transporting glucose. The uptake of α-MG, strictly observed at the apical side of the cells, was saturable as a function of time and almost completely inhibited by phlorizin, a nontransportable competitive inhibitor of the SGLT proteins as observed by Schaaf et al. (24). When sodium was omitted from the transport buffer and replaced by choline chloride, sugar uptake was only 18% of control values after 60 min, indicating that the observed α-MG transport is indeed sodium dependent. Note that a small amount of α-MG was still taken up in Na+-free conditions, which might represent passive diffusion of α-MG (23). Immunostaining showed the presence of both SGLT1 and SGLT2 in primary PTC. These subtypes of the SGLT family are expressed in different segments of the proximal tubule with SGLT1 being preferentially expressed in the S3 segment and SGLT2 in the S1/S2 segment. In our primary cultures, proximal tubule cells from both segments are present. These results demonstrate the presence of a sodium-dependent glucose transport at the apical membrane of our primary cultured cells.

The major advantage of culturing PTC on permeable supports is that in this way, their electrophysiological character-

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<th>Condition 1</th>
<th>Basal</th>
<th>No Na⁺</th>
<th>ΔNo Na⁺ − basal</th>
<th>%Decrease</th>
<th>Isc, µA/cm²</th>
<th>Gt, mS/cm²</th>
<th>Cf, µF/cm²</th>
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<tr>
<td>Basal</td>
<td>21.16±0.1</td>
<td>−2.15±0.1</td>
<td>23.31±1.0</td>
<td>110%</td>
<td>15.73±0.01</td>
<td>12.4±0.13</td>
<td>3.33±0.12</td>
</tr>
<tr>
<td>No Na⁺</td>
<td>−2.15±0.1</td>
<td>12.4±0.13</td>
<td>0.82±0.0005</td>
<td>21%</td>
<td>7.97±0.0001</td>
<td>0.03±0.0003</td>
<td>4%</td>
</tr>
<tr>
<td>ΔNo Na⁺ − basal</td>
<td>23.31±1.0</td>
<td>12.4±0.13</td>
<td>0.82±0.0005</td>
<td>21%</td>
<td>7.97±0.0001</td>
<td>0.03±0.0003</td>
<td>4%</td>
</tr>
<tr>
<td>%Decrease</td>
<td>110%</td>
<td>21%</td>
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Thus, the method enables us to isolate and grow highly differentiated primary cultures, which express distinct essential PT transport proteins.

By a simple spectrophotometric assay, we demonstrated the presence of alkaline phosphatase, an enzyme that catalyzes the hydrolysis of phosphate monoesters, and γ-glutamyl-transferase, an enzyme that catalyzes the transfer of a γ-glutamyl moiety of glutathione to a variety of α-amino acids. Freshly isolated proximal tubules were also analyzed since they resemble more closely the in vivo situation, so it is expected that enzyme activity is preserved as well. For both enzymes, the activity was lower in isolated PT compared with 7-day-old PTC. This difference might be due to the collapse of the tubular lumen during isolation (21), and therefore, only enzyme activities at the open ends are measured. However, surface markers, like brush-border enzymes, are known to be unstable during the transition from in vivo to in vitro (29). To characterize our cells functionally, we evaluated the transport of glucose at the apical membrane, another specific cellular function of PT cells. PT cells possess an apical membrane a sodium-dependent glucose transport system (9) ensured by the SGLT-protein (35). Using [14C]-α-methyl-D-glucopyranoside (α-MG), a stable glucose analog, we demonstrated that our primary cultures were capable of transporting glucose. The uptake of α-MG, strictly observed at the apical side of the cells, was saturable as a function of time and almost completely inhibited by phlorizin, a nontransportable competitive inhibitor of the SGLT proteins as observed by Schaaf et al. (24). When sodium was omitted from the transport buffer and replaced by choline chloride, sugar uptake was only 18% of control values after 60 min, indicating that the observed α-MG transport is indeed sodium dependent. Note that a small amount of α-MG was still taken up in Na⁺-free conditions, which might represent passive diffusion of α-MG (23). Immunostaining showed the presence of both SGLT1 and SGLT2 in primary PTC. These subtypes of the SGLT family are expressed in different segments of the proximal tubule with SGLT1 being preferentially expressed in the S3 segment and SGLT2 in the S1/S2 segment. In our primary cultures, proximal tubule cells from both segments are present. These results demonstrate the presence of a sodium-dependent glucose transport at the apical membrane of our primary cultured cells.

The major advantage of culturing PTC on permeable supports is that in this way, their electrophysiological character-
istics can be assessed in an Ussing-type chamber. Proximal tubule cells form a leaky epithelium possessing a high transport of Na\(^+\) and a typically low transepithelial resistance (R\(_T\)). In our primary cultured PTC, we measured a high I\(_{sc}\), which dropped immediately after replacing Na\(^+\) for NMDG in the Ringer solution, indicating that the current was completely carried by Na\(^+\) and that the Na\(^+\)-K\(^+\)-ATPase in the basolateral membrane is present and active. After replacing glucose for sucrose in the Ringer solution, a small drop in I\(_{sc}\) was observed, indicating that glucose is transported over the apical membrane in an electrogenic way, achieved by the presence of a sodium-dependent glucose cotransporter at the apical membrane. The drop in I\(_{sc}\) after glucose omission is smaller than the decrease in I\(_{sc}\) after Na\(^+\) deletion. This implies that other electrogenic Na\(^+\) cotransporters are present as well. The R\(_T\) was characteristically low (around 66 Ohm/cm\(^2\)). These results indicate that our cultured PTCs represent the typical electrophysiological characteristics of a leaky proximal tubule epithelium (34). The small drop in capacitance after omission of Na\(^+\) or glucose might be due to a drop in transport, resulting in a closure of the lateral intercellular spaces, as has been described previously by Van Driessche et al. (30) and Spring and Hope (27).

In conclusion, we have described a novel method to culture mouse PT cells on collagen-coated membranes with a reasonable yield. Electron microscopic analysis displayed a differentiated morphology of polarized cells with characteristics of PT cells. Furthermore, the presence of PT-specific proteins, such as water, ion, or glucose transporters; a receptor-mediated endocytosis of proteins; and efficient brush-border-associated enzymes demonstrated that these primary cells retained the differentiated functions of their in vivo counterparts for at least 3 to 4 days. Electrophysiological analysis revealed that these primary PTCs possessed all typical characteristics of a leaky proximal tubule epithelium with a high Na\(^+\) transport rate. Since these cultures were established on collagen-coated membranes, this method represents a useful tool to study a variety of proximal transport systems, as well as the influences of different substances like hormones at both the apical and the basolateral sides of the PT cell. Moreover, used in an Ussing chamber, the confluent monolayer allows us to study and follow the electrogenic transport characteristics online.

ACKNOWLEDGMENTS

We wish to acknowledge Prof. Van Driessche (Laboratory of Physiology, Katholieke Universiteit Leuven and Universiteit Hasselt, Belgium) for building the Ussing chamber. We thank Prof. Dr. J. Parys (Laboratory of Physiology, Katholieke Universiteit Leuven, Belgium) for his kind help and for making the liquid scintillation counter available to us. We also thank Prof. Dr. C. Jumarie (Université de Québec à Montréal, Montreal, Canada) from whom we received helpful advice, and the technical assistance of Y. Cnops (Division of Nephrology, Université Catholique de Louvain, Belgium), R. Beenard, J. Santermans, M. Jans, J. Janssen and P. Pirotte (all from Universiteit Hasselt).

GRANTS

F. Jouret and O. Devuyst are funded by Fonds de la Recherche Scientifique, Fonds de la Recherche Scientifique Médical, the Actions del Recherche Concertées 00/05-260, and the Fondation Forton.

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