A Novel Protein, Densin, Expressed by Glomerular Podocytes

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Abstract. With the recent molecular findings, the podocyte is emerging as a key cell type involved in glomerular damage, but protein complexes involved remain poorly understood. To systematically search for additional podocyte molecules interacting with nephrin, a key structural molecule of the interpodocyte filtration slit, precipitation of glomerular lysates was set out with anti-nephrin antibodies to identify members of the nephrin-associated protein complex. Proteins of the precipitate were subsequently identified with MALDI-TOF mass analysis. One of the proteins thus obtained showed identity with densin, a protein originally purified from rat forebrain postsynaptic density fraction and so far shown to be highly brain-specific.

The expression of densin appeared distinctly in the glomerulus and cultured podocytes by RT-PCR. Immunoblotting studies revealed a specific band of 185 kD in brain and cultured podocytes; in human glomerulus, densin appeared as a 210-kD band. By immunocytochemistry, densin localizes in glomeruli in a podocyte-like pattern. Electron microscopic studies revealed densin localization in the slit diaphragm area. Due to its known involvement in the synaptic organization, maintenance of cell shape and polarity in nerve cells, together with its demonstrated interactions with α-actinin-4, densin may share the same functions in podocytes by associating with the nephrin interacting protein complex at the slit diaphragm.

The ability of glomerular epithelial cells, podocytes, to form foot processes with unique intercellular slit diaphragms (SD) reflects a special organization with possible direct consequences for glomerular filtration. The protein complex forming the SD has been poorly known until the milestone discovery of NPHS1 (1), the gene encoding nephrin, which apparently forms the backbone of the SD (2–4). Thereafter, additional molecules with possible role in the maintenance of the functional filtration barrier have been rapidly found. These include e.g. the CD2-associated protein (CD2AP) (5), α-actinin-4 (6), podocin (7), P-cadherin (8), FAT (9), NEPH1 (10), and filrin (11). Two of these proteins, CD2AP and podocin, reportedly interact with nephrin (12–16), probably mediating the connection of the SD protein complex to the actin cytoskeleton (14,17). Other interactions of this complex remain to be shown.

The NPHS1 gene is characteristically mutated in the congenital nephrotic syndrome of the Finnish type (CNF) (1), resulting in the absence of nephrin. Clinically CNF presents with heavy, treatment-resistant proteinuria at or even before birth (18,19). CNF and nephrin thus offer a useful model disease and key molecule, respectively, to study molecular mechanisms of proteinuria and to search for additional components of the molecular complex.

Nephrin and podocin are associated with lipid rafts and mediate outside-in signaling (16,20). The resulting specific phosphorylation events most likely are involved in fine-tuning the functional properties of the SD (20). Through the binding of nephrin to podocin and CD2AP, specific signaling has been described suggesting that a proper molecular interaction network at the SD domain is essential to control the dynamic passage of fluids, electrolytes, and particularly proteins through the glomerular filtration barrier.

To search for additional molecules interacting with nephrin, we took an alternative approach by systematically co-precipitating glomerular lysates with anti-nephrin antibodies and identified the protein yields with mass spectrometry. Surprisingly, we detected a protein, densin, previously only found in the central nervous system (21). Densin belongs to a family of proteins known to function in cell adhesion and polarity (22). In addition to its first identification in the kidney, we here describe densin expression in glomerular podocytes as verified by RT-PCR, immunofluorescence, Western blotting, and immunoelectron microscopy. The results suggest that densin is an important component of a larger complex of proteins localized at the SD area with a proposed role in glomerular filtration.
Materials and Methods
Tissue Samples and Cell Culture
Renal tissue of CNF patients and cadaver kidneys unsuitable for transplantation for vascular anatomic reasons (Department of Surgery, University of Helsinki) or normal poles of kidneys removed because of Wilms tumor were used as described earlier (2). The cortical tissue was separated and frozen in liquid nitrogen and stored at −70°C until processed for RNA isolation or immunohistochemistry. Glomeruli were isolated with the sieving method as described earlier (23).
A sample of normal brain tissue adjacent to a tumor in the temporal lobe was from a young adult taken during tumor surgery.
All the procedures described were approved by the ethics committee of the Helsinki University Central Hospital.
Human podocytes were isolated from normal human kidney as earlier described extensively (24). The cultured cells showed an epithelial morphology and stained positively for Wilms tumor antigen (WT1) and nephrin in indirect immunofluorescence. These cells were negative for the endothelial cell marker, factor VIII related antigen.

Production of Antibodies to Nephrin and Densin
The whole intracellular sequence of rat nephrin (GenBank AF125521) was cloned to pGEX-2T expression vector (Amersham Pharmacia Biotech, Uppsala, Sweden) and transformed into the Escherichia coli strain BL-21 (Amersham Pharmacia Biotech) followed by culture in 2×YTAg medium (yeast extract 10 g/L, tryptone 16 g/L, NaCl 5 g/L, glucose 2%, and 100 μg/ml ampicillin) at 37°C for 4 h. After isopropyl β-D-thiogalactosidase (IPTG; Amersham Pharmacia Biotech) induction expression was allowed for 1 to 2 h before purification as described earlier (25). Shortly, the cells were lysed in STE buffer (150 mM NaCl, 10 mM Tris, pH 7.5, and 1 mM EDTA) in the presence of 100 μg/ml lysozyme, 3% sarcosyl, and 5 mM dithiothreitol following clearing with centrifugation at 7000×g at 37°C. Supernatant was adjusted to 2% with Triton X-100 before fusion protein collection was performed with HisTrap Kit (Amersham Pharmacia Biotech) induction expression was allowed for 1 to 2 h before purification as described earlier (25). Shortly, the cells were lysed in STE buffer (150 mM NaCl, 10 mM Tris, pH 7.5, and 1 mM EDTA) in the presence of 100 μg/ml lysozyme, 3% sarcosyl, and 5 mM dithiothreitol following clearing with centrifugation at 7000×g. Supernatant was adjusted to 2% with Triton X-100 before fusion protein collection was performed with HisTrap Kit (Amersham Pharmacia Biotech). The eluted protein was used for immunizations. The respective number of the antiserum produced with this antigen is #050.
To produce antibodies against soluble nephrin, human nephrin sequence (GenBank AF 035835) 3091–3645 lacking the membrane-spanning exon 24 (GenBank AF126957) was first inserted into donor vector pUni/V5-His-TOPO (Invitrogen, Carlsbad, CA) followed by fusion to acceptor vector pBAD/Thio-E Echo (Invitrogen) according to manufacturer’s protocol. This thioredoxin fusion construct was transformed to TOP10 Escherichia coli strain for further culturing in LB medium with added kanamycin 50 μg/mL. Expression was induced with 0.02% arabinose followed by production at 37°C for 4 h. Collected cells were lysed with 100 μg/ml lysozyme, sonication, and flash freezing in the presence of the Complete Mini EDTA-free protease inhibitor mix (Roche, Mannheim, Germany). Purification was performed with HisTrap Kit (Amersham Pharmacia Biotech) using nickel as binding cation for coupling the fusion protein. Bound protein was eluted using an imidazole step gradient from 40 to 300 mM. The antiserum against this human antigen used is #1109.
To obtain antiserum, rabbits were immunized with standard protocol. This thioredoxin fusion construct was transformed to TOP10 Escherichia coli strain for further culturing in LB medium with added kanamycin 50 μg/mL. Expression was induced with 0.02% arabinose followed by production at 37°C for 4 h. Collected cells were lysed with 100 μg/ml lysozyme, sonication, and flash freezing in the presence of the Complete Mini EDTA-free protease inhibitor mix (Roche, Mannheim, Germany). Purification was performed with HisTrap Kit (Amersham Pharmacia Biotech) using nickel as binding cation for coupling the fusion protein. Bound protein was eluted using an imidazole step gradient from 40 to 300 mM. The antiserum against this human antigen used is #1109.

Sample Preparation for MALDI-TOF-MS Analysis
Fingerprinting for trypsinized peptides was performed with a Bi-flex matrix-assisted laser desorption/ionization-time of flight (MALDI-TOF) mass spectrometry (2 GHZ digitizer; Bruker, Rheinstetten, Germany) at a local protein chemistry unit (Biomedicum, University of Helsinki). Positive ion reflector mode was used with an accelerating voltage of 19,000 V and delayed extraction of 2 ns. Internal peptide calibration standards (Bruker Daltons, Bremen, Germany) were applied to obtain higher peptide mass accuracy.

RT-PCR
The reverse transcription and semiquantitative RT-PCR was performed as described earlier from this laboratory (30).
PCR for densin cDNA was performed with primers (sense 2485U 5’-AGCTTTCCTCGAACATGG-3‘, antisense 2692L 5’-GGTG-TGTTGAGGCTGACTG-3‘) designed according to the rat densin sequence (Gen Bank U66707). The same primers were used for human and rat cDNA due to only two-base difference inside the primer regions with no changes at the 3′ end of the primers. To verify the amplification results, another human sequence (AF434715) specific primer pair (sense 3754U 5‘ GAC AAG CCA TCA GAT AAC A 3‘; antisense 4641L 3‘ AGT TGC ACT CGA ATG ACA G 3‘) were used. Amplification program included denaturation at 94°C followed by a 35 cycles with 30 s at 94°C, 30 s at 56°C, and 30 s at 72°C. After the last cycle, elongation at 72°C for 10 min was allowed.
**Immunoblotting**

Western blotting and semiquantitation of the densin protein was done essentially as described earlier from this laboratory (31). Affinity-purified polyclonal rabbit anti-densin antibody directed to the putative extracellular part of densin was used at 1:1000 dilution followed by an incubation with the horseradish peroxidase–conjugated affiniPure goat anti-rabbit IgG (H+L; Jackson Immuno Research Laboratories Inc., West Grove, PA) at 1:50000. Visualization of the bound antibodies was done using SuperSignal West Pico Chemiluminescent Substrate kit (Pierce, Rockford, IL), Broad-Range Prestained SDS-PAGE Standard (Catalog 161–0318; Bio-Rad Laboratories, Hercules, CA) as used as a molecular size marker.

**Immunofluorescence**

Normal human and CNF kidney cortical tissue samples were prepared for immunofluorescence as described earlier (32). Briefly, 5-μm frozen cortical sections were fixed in acetone and incubated with the primary antibodies diluted in 10% normal human serum. The affinity-purified tetramethylrhodamine (TRITC)–conjugated goat anti-rabbit Ig (Jackson Immuno Research Laboratories Inc.) was used as second antibody for anti-densin antibodies and FITC-conjugated AffiniPure goat anti-mouse Ig (Jackson Immuno Research Laboratories Inc.) for mouse monoclonal podocalyxin antibody PHM5 (Dakopatts, Glostrup, Denmark) (used for internal control of tissue reactivity and preservation). Immuno-Mount embedding medium (Shandon, Pittsburgh, PA) covered sections were analyzed with an Olympus OX50 microscope equipped with appropriate filter systems for TRITC and FITC (Olympus Optical GmbH, Hamburg, Germany) fluorescence. The semiquantitative analysis was done by two independent observers.

**Immunoelectron Microscopy**

Immunoelectron microscopy was done as described earlier (33). After fixation of normal cortex in 4% formaldehyde and embedding with Lowicryl K4M (Chemische Werke LOW1, Waldkraiburg, Germany), 1-micron-thick sections were cut. The sections were blocked with ovalbumin followed by incubation with affinity-purified anti-densin antibodies and the relevant 10-nm gold conjugate (1:50). Cryo EM was performed with the same antibodies.

**Results**

**Characterization of Nephrin Antibodies**

Antisera #050 and #1109 were tested for specificity to nephrin by immunoblotting and immunoprecipitation using lysates of isolated glomeruli (Figure 1, A and B). A clear 185-kD band was detected in immunoblotting studies and in immunoprecipitations followed by immunoblotting with another anti-nephrin antibody. Furthermore, preincubation with the corresponding immunizing antigen blocked the blotting reaction. Antibodies were also tested on kidney cortical sections with immunofluorescence assay revealing distinct reactivity exclusively within glomeruli in a typical manner (data not shown).

**Peptide Fingerprint and Data Bank Search**

The list of peptide masses obtained in MALDI-TOF-MS analysis was used to search the NCBI database using ProFound software (Version 4.10.5, Rockefeller University). Of the peptide masses obtained, 11 matched with rat densin covering 10% of the 1495-long amino acid sequence.

**RT-PCR**

RT-PCR analysis for densin revealed specific mRNA expression in glomeruli as well as in cultured human podocytes (Figure 2). Amplification of the cDNA prepared from rat brain tissue gave a band of the same size when the samples were run in 1.5% agarose gel. Results were confirmed by sequencing the amplified PCR products of brain and podocytes revealing 100% identity with densin. Semiquantitative RT-PCR study revealed increased densin mRNA expression in CNF kidney cortex when compared with normal human cortex (Figure 4A).
Immuno blotting

In immunoblotting experiments, the appropriate cell and tissue lysates were blotted with affinity purified anti-densin antibodies raised against the extracellular part of human densin (Figure 3A). These experiments revealed the typical band of 210 kD in human glomerular lysate, while a 185-kD band was obtained in the lysate of human podocytes. Also, blotting of human brain lysate revealed the same 185-kD band as was described earlier in rat brain lysate (27). Increased densin protein expression was detected in CNF glomeruli by semi-quantitative immunoblotting (Figure 4B).

Co-Immunoprecipitations

After precipitation with anti-nephrin antibody #1109 of human glomerular lysate, the resulting precipitate was separated on SDS-PAGE followed by Western blotting using affinity-purified anti-densin antibody. This revealed a densin-specific band of the size of 210 kD, while no such band was observed from glomerular lysate incubated with Protein A Sepharose 4B only (Figure 3B).

Immunofluorescence and Electron Microscopy

Immunofluorescence studies of semi-thin frozen section revealed intensive glomerular staining of podocytes (Figure 5, A and B) and faintly also in proximal tubuli (Figure 5C). In CNF glomeruli, anti-densin antibodies showed reduced staining. Staining intensity with anti-podocalyxin antibodies was equal in both CNF and normal tissues (Table 1). In immunoelectron microscopy (Figure 6, A, B, and C), gold particles were seen in close association with the slit diaphragm domains.

Discussion

Here we report of a new molecular component, densin, in the kidney glomerular podocytes. This molecule was discovered in the systematic search for new nephrin-associated molecules from human glomeruli using precipitation with anti-nephrin antibody and followed by mass spectrometric identification.

In addition to previously reported expression in the brain, our results here show densin mRNA and protein distinctly in the kidney glomeruli and cultured podocytes. According to the amino acid sequence, the calculated molecular weight of densin is 167 kD. However, in immunoblotting experiments the size of densin appeared to be 185 kD in the human and rat brain as well as in human podocytes. In the human glomerulus the molecular size of densin, however, was 210 kD. The differences in the molecular weights observed are most likely due to tissue-specific posttranslational modifications, because densin belongs to the O-sialoglycoprotein family abundant in sialic acids (21). Another postsynaptic density (PSD) protein, synaptopodin, is similarly shared by the podocytes and the brain with slightly differing molecular weight in these tissues due to tissue-specific glycosylation patterns (34). In immunofluorescence studies, anti-densin antibody shows strong reactivity in podocytes and faintly also in the proximal tubular brush border area. Whether the observed tubular expression reflects true in situ functional densin or is due to leakage of soluble densin into urine much like nephrin (35) followed by tubular reabsorption remains to be studied in detail.

Immunoelectron microscopic studies revealed densin, particularly at the slit diaphragm domain (Figure 6). Interestingly, our results showed increased densin mRNA and protein expression by semiquantitative RT-PCR and Western blotting in

![Figure 3](image3.png)

**Figure 3.** (A) Immunoblotting of human (1) brain, (2) cultured podocytes, and (3) glomerular lysates with affinity-purified antibodies to the extracellular domain of densin. A band at around 180 kD can be seen in brain and podocytes, whereas band of an approximate size of 210 kD in the glomeruli is obvious. Molecular mass markers indicated on the left. (B) Human glomerular lysate immunoprecipitated with anti-nephrin antibody #1109 shows co-precipitation of densin. Such precipitation with Protein A sepharose 4B is not seen.

![Figure 4](image4.png)

**Figure 4.** Semiquantitative RT-PCR and Western blotting of normal (NH) and CNF kidney. (A) Increased densin mRNA expression is seen in CNF cortex. (B) Upregulation of densin protein in CNF as shown by immunoblotting with anti-densin antibodies.

![Figure 5](image5.png)

**Figure 5.** Indirect IF of 1-μm frozen sections shows specific staining of podocytes (A and B; arrowheads) around capillary lumen (CL). The signal was also detected from brush border of proximal tubuli (C).
We were able to precipitate densin with anti-nephrin antibodies from rat glomerular lysates as well as from human glomerular lysates (Figure 3B). The absence of densin from the lipid rafts raises the question whether the interaction of nephrin and densin is due to interaction via a larger protein complex or with the non-lipid raft associated form of nephrin. The first proposal is supported by the fact that in the lysate most of the membrane proteins are still insoluble and larger membrane complexes remain in the supernatant allowing precipitation of proteins without direct interactions. However, the second possibility cannot be ruled out, as it is known that a low detergent concentration preserves most of the protein-protein interactions.

Densin belongs to the LAP (leucine-rich repeats [LRR] and PDZ domains) protein family (21). LAP proteins have thus far been found in specialized epithelia and postulated to be involved in the maintenance of cell shape and the apical-basal polarity (22). These would be the prime candidate functions of densin also in the podocytes. Podocytes can similarly be divided into distinct apical and basal compartments along the division plane of the slit diaphragm. Densin may thus be one of the important molecules needed for the maintenance of podocyte polarity. In neuronal cultures, densin localizes mainly at the site of cellular synapses (21). The proposed function of densin in bridging presynaptic to postsynaptic membranes in the glutamatergic synapses (21) also remains intriguing; the physical dimensions match closely with the interpodocyte distance separated by the slit diaphragm. Homotypic adhesion found in some LRR-containing proteins also resembles the proposed functions of nephrin as an interpodocyte spacer. Typical function for the type I PDZ domains is binding to distinct C-terminal sequences of other proteins. It is of particular interest that the newly proposed additional component of the slit domain, FAT (9), contains the typical three C terminal amino acids (TEV) interacting with the PDZ I type domains (9,38,39).

Also podocalyxin and megalin, abundant proteins of podocytes, have this sequence at their C terminus. Podocalyxin as a new proposed additional component of the slit domain, FAT (9), contains the typical three C terminal amino acids (TEV) interacting with the PDZ I type domains (9,38,39).

Table 1. Semiquantitative immunofluorescence analysis shows reduced staining with anti-densin antibodies in CNF glomeruli when compared with normal glomeruli (NH) using an end point titration with antibody dilutions as indicated.

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Table 1. Semiquantitative immunofluorescence analysis shows reduced staining with anti-densin antibodies in CNF glomeruli when compared with normal glomeruli (NH) using an end point titration with antibody dilutions as indicated.

CNF glomeruli (in which the SD is missing) when compared with normal glomeruli (Figure 4), whereas the glomerular immunostaining for densin was reduced (Table 1). This apparent controversy may reflect an abnormal distribution and localization of densin in the severely distorted and flattened podocytes in CNF glomeruli missing the nephrin backbone for proper anchoring. With missing feedback control, this led to overproduction and dispersed localization within the podocyte and functional association with nephrin.

The transmembrane nature of nephrin with an extracellular and a characteristic intracellular domain has been shown to reflect functionality. The extracellular domain most likely mediates outside in signaling (20). The intracellular part of nephrin has no marked similarity to other known proteins and, according to recent evidence, mediates binding to the cytoskeleton via CD2AP (12,13). Association with podocin (16) suggests that the many cytoplasmic proteins of podocytes converge to form the SD with its nephrin backbone (36). This kind of compartmentalization to functional domains has been proposed previously (37) and is directly supported by recent findings (31). Nephrin association preferentially to SD and particularly in the lipid rafts like in many proteins of the central nervous and immunologic systems may suggest of some yet unidentified shared functions. Here we did not find densin association in the detergent-resistant membrane fractions, e.g., lipid rafts, but instead in the high-sucrose fractions after sucrose gradient centrifugation of glomerular lysate. The main pool of nephrin is also seen in the high-sucrose fractions (data not shown). We were able to precipitate densin with anti-nephrin antibodies from rat glomerular lysates as well as from human glomerular lysates (Figure 3B). The absence of densin from the lipid rafts raises the question whether the interaction of nephrin and densin is due to interaction via a larger protein complex or with the non-lipid raft associated form of nephrin. The first proposal is supported by the fact that in the lysate most of the membrane proteins are still insoluble and larger membrane complexes remain in the supernatant allowing precipitation of proteins without direct interactions. However, the second possibility cannot be ruled out, as it is known that a low detergent concentration preserves most of the protein-protein interactions.
linking of densin to the actin-cytoskeleton. Interestingly, mutations in the ACTN4 gene lead to familial focal segmental glomerulosclerosis (FSGS) (6), showing its importance in maintaining podocyte stability.

One of the most widely used methods in protein interaction studies is yeast two-hybrid screening. However, this method has obvious limitations, including autoactivation for some target molecules. For nephrin intracellular domain, repeated experiments either with the full-length intracellular domain or after using only the known interaction domains of it constantly resulted in autoactivation and thus did not produce reliable results. Here the alternative to yeast-two-hybrid screening, the coprecipitation method to pull down interaction partners appeared highly useful. For the subsequent molecular identification mass spectrometry was used. The data show that true in vivo protein interactions can be detected with this approach, without cDNA cloning and recombinant protein production steps.

The choice of tissue lysis conditions, including the choice of buffer system, plays a critical role in co-precipitation studies. High salt content and choice of strong detergents will release transmembrane proteins, but most in vivo interactions may be lost. On the other hand, weak buffer conditions may not reach proper solubilization and precipitation of many membrane-bound proteins. Thus, a compromise in the lysis conditions is inevitable. With the chosen conditions combined with the MALDI-TOF analysis, we could identify ten potential interactors, however, not including the thus far reported proteins linking of densin to the actin-cytoskeleton. Interestingly, mutations in the ACTN4 gene lead to familial focal segmental glomerulosclerosis (FSGS) (6), showing its importance in maintaining podocyte stability.

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