Evidence for the existence of multiple heparan sulfate proteoglycans in the human glomerular basement membrane and mesangial matrix

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Heparan sulfate proteoglycans (HSPGs) are essential components of the glomerular basement membrane (GBM) carrying a strong anionic charge. A well-characterized extracellular HSPG is perlecan, ubiquitously expressed in basement membranes. A cDNA construct encoding domains I and II of human perlecan was expressed as a fusion protein with glutathione S-transferase. This fusion protein was used to generate monoclonal antibody 9S110. We compared the staining pattern of 9S110 with that of M215, a previously prepared mAb that recognizes HSPG isolated from human GBM. In kidney cortex, the anti-perlecan mAb 9S110 showed a strong staining of the mesangium, Bowman’s capsule, the tubular basement membrane, and stained the GBM only slightly. In contrast, M215 predominantly stained the GBM in a linear fashion. Immunoelectron microscopy supported these results, showing concentrations of perlecan in some regions of the GBM, whereas the unidentified M215 antigen was homogenously distributed throughout the GBM. In other human tissues, both antibodies also produced a different staining pattern. Furthermore, a polyclonal antisera recognizing HSPG isolated from the GBM did not recognize perlecan from EHS tumors. These results provide evidence for the presence of another HSPG in the GBM that is immunologically distinct from perlecan. The absence of perlecan splice variants in the kidney suggests that this component is encoded by a different gene than perlecan. Given its marked expression in the GBM, this component could be a determining factor in the maintenance of selective glomerular permeability.

Keywords: perlecan; heparan sulfate proteoglycan; prokaryotic expression; glomerular basement membrane.
perlecan, suggesting that they are generated by proteolytic processing [23].

Previous immunofluorescence studies performed with various monoclonal and mononuclear antibodies yielded inconsistent results, with particular differences in the staining intensity of the GBM [3, 9, 11, 24, 25]. For the generation of mAbs, prokaryotic expression offers a large advantage over proteoglycan extraction from basement membranes, because the risk of co-immunization with contaminating HSPG species is eliminated. Furthermore, recombinant protein expression allows the development of domain-specific antibodies. We have synthesized domains I and II of human perlecan as a bacterial fusion protein and generated monoclonal antibody 95J10. In this study, we compare the expression pattern in human tissues for 95J10 and M215, a mAb that was previously raised against isolated human GBM-HSPG [3]. The results provide evidence for the presence of an unidentified HSPG in the GBM, which appears to be immunologically distinct from perlecan.

EXPERIMENTAL PROCEDURES

Materials. The following were obtained from the indicated sources: pGEX4T-3 expression vector, glutathione-conjugated Sepharose 4B (Pharmacia Biotech); reduced glutathione (Boehringer Mannheim), pCR-Script cloning vector, Sf9 (Strategene Cloning Systems); isopropylthio-β-D-galactoside, T4 DNA ligase, Neol, BanHI (Life Technologies); Vent polymerase, NorI, XcmI (New England Biolabs); thermal cycler apparatus (Perkin Elmer); automated sequencer (Applied Biosystems); thrombin, phenylmethylsulfonyl fluoride, ribonuclease A (Sigma), 2-iodoacetamide (Merck); N-ethylmaleimideimide, EDTA (Fluka Chemie); benzamidine hydrochloride (Janssen Chimica); 6-aminohexanoic acid (Aldrich); Tween-20 (ICN Biomedicals); Immobilon-P, ultrafiltration units (Millipore); goat-anti-mouse peroxidase conjugate (Dako) sheep-anti-mouse fluorescein isothiocyanate conjugate (Cappel, Oss, The Netherlands); [γ-32P]ATP, ECL detection kit (Amersham).

Construction of the expression vector pGEX4T3-P12a. A prokaryotic expression vector encoding amino acids 24–404 of human perlecan was prepared as follows. Two PCR products were generated by using CDNA clone Hpe2 [16] using Vent polymerase for proofreading activity. The primer sets were: 5′-TCA-TCTCCAGCGCTTCTG-3′ (forward P1), 5′-TCTATGGGACCTGCGCCCTTC-3′ (reverse P1), 5′-TCTATCCAGCGCTTCTG-3′ (forward P2) and 5′-TTCTATGAGCCAAACTCTG-3′ (reverse P2, this primer introduces an in-frame stop codon immediately behind amino acid 404). The two PCR products were inserted into the Sf9 cloning site of pCR-Script [26, 27] and screened to detect the unique NorI site at the 3′-end of the CDNA fragments. The P2 fragment was then ligated to the P1 fragment by use of the XcmI restriction site, introduced into pGEX4T3-3 [28] using the Neol and NorI cloning sites. The fidelity of amplification and ligation procedures was checked by sequence analysis. The resulting expression vector was named pGEX4T3-P12a.

Expression and purification of recombinant perlecan-(24–404)-peptide. Expression of the recombinant perlecan-(24–404)-peptide was performed as described in [28], except that the cell pellet was resuspended in 125 mL ice-cold NaCl/P, (140 mM NaCl, 2.7 mM KCl, 10 mM NaHPO4, 2 mM KH2PO4, pH 7.5), 1% Triton X-100, 10 mM N-ethylmaleimide, 5 mM EDTA, 10 mM 6-aminohexanoic acid, 5 mM 2-iodoacetamide, 1 mM phenylmethylsulfonyl fluoride and 1 mM benzamidine/HCl. Cell lysis and affinity purification of the recombinant fusion protein were performed in the presence of 1% Triton X-100, which was essential for optimal yields. In contrast, the yield could not be improved by other modifications of the procedure such as the use of sarcosyl for solubilization [29], growth at 30°C [30] or treatment with Mg2+ and ATP prior to affinity chromatography [31].

Affinity-purified fusion protein was incubated with 1.7 NHU/mgl human thrombin (specific activity approximately 4000 NHU/μg) and incubated for 60 min at 22°C. To exhaustively remove the thrombin-digested mixture from the glutathione-Sepharose 4B column (1 mL) at room temperature. The flow-through was concentrated by ultrafiltration against a 10-kDa cutoff membrane to a final concentration of 0.63 mg/mL (determined by the Bradford method with BSA as reference) [32].

Antibodies. The anti-perlecan mAb 95J10 was prepared as follows. Mice were immunized and boosted with 20 μg purified perlecan-(24–404)-peptide per injection (this preparation was completely devoid of GST). Hybridoma cell lines were screened by ELISA with an isolated batch of recombinant fusion protein. Twelve positive clones were examined in indirect immunofluorescence studies for their capacity to stain human renal basement membranes. A mAb designated 95J10 was selected that showed strong glomerular staining. The mAb also reacted in western blot analysis with the fusion protein and with perlecan-(1–404)-peptide expressed by baculovirus-infected insect cells [33], which indicated that it also recognizes the antigen in a denatured conformation. No cross-reactivity of mAb 95J10 with Escherichia coli proteins or GST was observed by ELISA and western blotting. Experimental animal care, cell fusion, and generation of the monoclonal hybridoma cell line 95J10 were performed by Diabor Ltd, Oulu, Finland.

Other antibodies used were R254 (a rat mAb against mouse perlecan; a generous gift of Dr J. van den Bom), M215 (a mouse mAb against the core protein of HSPG isolated from human GBM [3]), and K42 (a rabbit antisera recognizing HSPG from the human and murine GBM [9]).

Immunological methods. SDS/PAGE and immunoblot analyses were carried out following standard procedures [30]. All samples were desalted by boiling in the presence of 2-mercaptoethanol prior to loading onto a homogeneous 5% polyacrylamide gel. Immunofluorescence and tissue distribution studies were performed with adult human tissue specimens obtained during autopsy, snap-frozen in liquid nitrogen and stored at −80°C until use. Cryostat sections of 2 μm were attached to glass slides and treated with acetone for 10 min at 4°C for fixation. mAb M215 or 95J10 was applied as undiluted hybridoma supernatant. After 1 h incubation at 22°C, specimens were submerged five times in fresh NaCl/P, for washing. Bound primary antibody was detected by incubating with fluorescein-isothiocyanate-conjugated sheep-anti-mouse immunoglobulins (30 min at 22°C in the dark). After thorough washing with fresh NaCl/P, the preparations were examined with a Leitz immunofluorescence microscope. For immunoelectron microscopy, kidney cortex slices were fixed with periodate-lysine-paraformaldehyde, immersed in 2.3 M sucrose for cryoprotection and snap-frozen in liquid nitrogen. Staining of peroxidase-conjugated antibody complexes was performed following standard protocols [34] and the sections were postfixed in Epon 812. Thin sections were examined with a Jeol 1200 EX electron microscope.

Northern hybridization. A multiple human tissue northern blot (Clontech Laboratories Inc.) was treated according to the supplier’s protocol with an antisense probe homologous to exon 3 of perlecan (5′-AAGTCCCCGCTGGCCAGTCCCCACTG-GCCAGGTCTG-3′) [20]. This exon is a prerequisite for the
presence of the HS chains. After hybridization, the filter was washed for 3 × 15 min under stringent conditions (15 mM NaCl, 1.5 mM sodium citrate, 0.1% SDS, pH 7.0 at 50°C) and exposed for autoradiography for 91 h.

RESULTS

Expression of perlecain domains I and II as a fusion protein with GST. A cDNA construct was prepared encoding domains I and II of human perlecain, fused to the carboxyl end of GST from *Escherichia coli* [28]. For localization of the recombinant protein, we tested the cell lysate, the culture supernatant, and the inclusion bodies isolated from the bacteria. The recombinant protein was found exclusively in the cell lysate. Crude extracts were analyzed by SDS/PAGE and immunoblotting with an anti-GST mAb (Fig. 1), confirming the presence of a recombinant fusion protein. Although the fusion protein was expressed at a level of 1.3 ± 0.3 mg/l crude culture (mean ± SD, n = 4), only 120 µg/l could be recovered by affinity chromatography. The affinity-purified fraction did not appear as a single band on SDS/PAGE, but contained multiple proteins as shown in lane 3 (Fig. 1). The largest of these proteins appeared as a strong band, which corresponded to the predicted molecular mass of 68 kDa. The observed additional bands and the low final yield suggest sensitivity of the fusion protein to proteolysis.

The GST fragment was removed from the hybrid protein utilizing an engineered recognition site for thrombin cleavage, and an additional round of affinity chromatography. Coomassie brilliant blue staining of the recombinant perlecain-(24–404)-peptide preparation identified two bands of 26 kDa and 19 kDa in size (Fig. 2, lane 5). The staining signal is weak compared to the GST fraction (Fig. 2, lane 6), which indicated a relatively low protein concentration. These results likely reflect proteolytic degradation of the fusion protein, also observed in lane 3 (Fig. 1 and 2). The final preparation, completely devoid of GST as shown in Fig. 1 (lane 5), was used to generate the monoclonal antibody mAb 95110.

**HSPG distribution in the human kidney.** In indirect immunofluorescence studies on human kidney cortex, mAb 95110 displayed a bright staining of the mesangium, Bowman’s capsule, the tubular basement membrane, and peritubular capillaries (Fig. 3B). The overall staining of the GBM was weak and visible only along fragments of the glomerular capillaries. In the arteriole, an intense staining was observed in intima, media, and adventitia (Fig. 3). The staining was especially pronounced at the luminal border. The staining was compared with that of another mAb designated M215. This mAb was obtained by immunization with HSPG purified from isolated human GBM, and is directed against an epitope of the core protein [3]. mAb M215 showed a strong linear staining of the GBM in immunofluorescence studies (Fig. 3D), along with a less intense but also linear staining of all other renal basement membranes (Bowman’s capsule, the tubular basement membrane, and the basement membranes of the peritubular capillaries). mAb M215 did not stain the mesangial matrix. In contrast to 95110, vascular staining of M215 was restricted to the endothelial border (Fig. 3C).

The ultrastructural distribution of HSPGs in the GBM was analyzed by immunoelectron microscopy with both mAbs (Fig. 4). The anti-perlecain mAb 95110 stained the GBM along some fragments of the capillary wall, whereas other regions showed no staining at all (Fig. 4A). In all cases, the staining was clustered at the endothelial side of the basal lamina (Fig. 4C). Besides the local accumulation of perlecain in the GBM, an elevated expression was seen in the mesangial matrix (Fig. 4A). M215, however, produced a homogenous staining along the entire length of the GBM (Fig. 4B and D). The clustered appearance of perlecain, and the linear distribution of non-perlecain GBM-HSPG, agree with the results from immunofluorescence studies.

**HSPG distribution in human tissues.** Adjacent sections of human tissues were stained for perlecain (mAb 95110) and non-perlecain GBM-HSPG (mAb M215). We especially focused on tissues that clearly displayed different staining patterns in indirect immunofluorescence studies using both mAbs. Fig. 5 shows typical results in skin, pancreas, artery, tongue, and cerebrum. Both antibodies stained the epidermal basement membrane in the skin (Fig. 5A and F), in addition, mAb 95110 stained the capillaries more intensely than M215. In the pancreas, mAb

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**Fig. 1.** Western blot detection of recombinant fusion protein with a GST-specific monoclonal antibody. Lane 1, crude cell extract of bacteria carrying the plasmid pGEX4t3; lane 2, crude cell extract of bacteria carrying pGEX-t3-P12a; lane 3, affinity purified preparation of the fusion protein; lane 4, thrombin-digested fusion protein; lane 5, perlecain-(24–404)-peptide fragments obtained from thrombin-digested fusion protein; lane 6, GST fragment obtained from thrombin-digested fusion protein. The positions of marker proteins are given on the left (kDa). Arrows on the right indicate the fusion protein in lanes 2 and 3 (FP) and the GST fragment in lanes 4 and 6.

**Fig. 2.** SDS/PAGE analysis of recombinant protein produced by recombinant *E. coli*. Recombinant protein was extracted from *E. coli*, purified by glutathione affinity chromatography and digested with thrombin. Proteins were separated by SDS/PAGE (12.5% polyacrylamide) and stained with Coomassie brilliant blue. M, marker lane; molecular mass indications are given on the left (kDa). The contents of lanes 3–6 are as described in Fig. 1.
Fig. 3. Immunofluorescence detection of heparan sulfate proteoglycans in the human renal cortex. Cryosections were stained for perlecan (A, B) and non-perlecan GBM-HSPG (C, D) using the mAbs 95J10 and M215, respectively. The asterisk in A indicates the tunica media of the arteriole; the arrow in B indicates the Bowman’s capsule; the arrowhead in C indicates autofluorescence typically originating from the elastica interna of the arteriole. Magnifications are 150X (A, C) and 400X (B, D).

Fig. 4. The ultrastructural localization of HSPGs in the glomerular basement membrane. Human kidney cortex was stained for perlecan (A, C) and non-perlecan GBM-HSPG (B, D), using mAbs 95J10 and M215 and was examined by immunoelectron microscopy. The arrowhead in A shows elevated levels of perlecan in the mesangial matrix. The arrowhead in C shows a typical condensation of perlecan on the endothelial side of the GBM. The arrowhead in D shows the homogenous linear distribution of non-perlecan GBM-HSPG. Magnifications were 5000X (A, B) and 15 000X (C, D).
Fig. 5. Indirect immunofluorescence staining of HSPGs in various human tissues. Cryosections were stained with mAbs 95J10 (A–E) or M215 (F–J). A and F: skin (arrow indicates epidermal basement membrane); B and G, pancreas (in B arrow indicates sinusoids and arrowhead indicates capillary. In G, arrow indicates capillary). C and H, artery (M, media; A, adventitia). D and I, tongue (arrow indicates skeletal muscle fibers; arrowhead indicates capillary; N, nerve fibers). E and J, cerebrum (in E, arrow indicates vein; asterisk indicates artery. In J, arrow indicates capillary). Magnifications were 100× (C, E, H, J), 150× (A, D, F, I), and 400× (B, G).

95J10 (Fig. 5B) displayed a strong staining of the sinusoids, the islets of Langerhans, and the capillaries whereas mAb M215 (Fig. 5G) only stained the capillaries. In arteries, 95J10 (Fig. 5C) stained the media and adventitia with vaso vasorum, reflecting the basement membrane distribution surrounding the smooth muscle cells. In contrast, the staining by mAb M215 was confined to the vasa vasorum (Fig. 5H). In cryosections from human tongue, mAb 95J10 (Fig. 5D) strongly recognized the...
endomysium that surrounds the skeletal muscle fibers, the capillaries, an artery, nerve fibers with a myelin sheath, and perineurium (bundles are surrounded by connective tissue). In contrast, mAb M215 stained only the capillaries (Fig. 5J). In cerebrum, 95J10 strongly stains veins in the cerebral cortex, the arteries, and the capillaries. In the same tissue, mAb M215 only stains the capillaries (Fig. 5J). In all cases, the specificity of the staining was checked by parallel incubations without the primary antibody.

The results obtained by immunohistochemistry suggest the occurrence of two different GBM-associated HSPG species. Could the observed differences be based on different epitope accessibilities in vivo? To exclude this possibility, preparations of HSPG isolated from the human GBM and from the mouse EHS tumor were analyzed by western blotting (Fig. 6). The EHS tumor is known to produce large amounts of perlecan. Using a rabbit polyclonal antiserum (K42) that recognizes both murine and human GBM-HSPG [9], no staining of EHS-HSPG was detected. Staining with mAb M215 gave identical results (data not shown). As a control for the transfer of EHS-HSPG to the blot, an identical treatment with a rat mAb against mouse perlecan resulted in a marked staining of EHS-HSPG. mAb 95J10 could not be used for this purpose, since it is specific for human perlecan. The specificity of antiserum K42 for GBM-HSPG, without any cross-reaction with perlecan, confirms that the two HSPG species are immunologically unrelated.

Perlecan splice variants occur in brain, placenta and skeletal muscle but not in kidney. Elucidation of the perlecan gene structure showed the theoretical possibility of alternative splicing [16, 17, 20]. Interestingly, the occurrence of splice variants would result in the expression of perlecan isoforms. We therefore investigated the occurrence of perlecan splice variants by northern blotting (Fig. 7). The full-size messenger RNA (approximately 14 kb) was detected in heart, placenta, skeletal muscle, kidney and pancreas, but was hardly or not at all present in brain, lung, and liver. Interestingly, a smaller size mRNA species was detected in brain (2.5–2.6 kb), placenta (1.9 kb and 6.4–6.7 kb) and skeletal muscle (3.1–3.3 kb). The significance of these molecules is not clear. In the kidney, however, we could not distinguish any splice variants.

**DISCUSSION**

As the presence of strongly anionic HSPGs is important to maintain the selective permeability of the GBM, the identification of perlecan as a basement-membrane-associated HSPG has provoked many investigators to study perlecan expression levels during nephropathy. We used mAb 95J10, directed against amino acids 22–404 of human perlecan, to analyze the distribution of perlecan in the glomerulus in more detail. The staining pattern of 95J10 in indirect immunofluorescence is in agreement with the results obtained by immunohistochemistry. The presence of strongly anionic HSPGs, as shown by silver staining, indicates that perlecan is a major component of the GBM. The presence of a rat mAb recognizing mouse perlecan (Fig. 5B) suggests that mouse perlecan can be used as a marker for the GBM.

**Fig. 6.** Comparative immunoblot analysis of HSPGs from glomerular basement membrane and EHS tumor. Equal quantities of HSPG isolated from the human GBM (lanes 1) and from the mouse EHS tumor (lanes 2) were separated by SDS/PAGE (5% polyacrylamide). Both HSPGs were analyzed by silver staining (A) and immunoblotting (B). For immunoblotting, we used K42 (a rabbit pAb that recognizes GBM-HSPG from mouse and man; left part of B) and R254 (a rat mAb recognizing mouse perlecan; right part of B).

**Fig. 7.** Northern blot analysis of mRNA of various human tissues. Poly(A)-rich mRNA isolated from heart (1), brain (2), placenta (3), lung (4), liver (5), skeletal muscle (6), kidney (7), and pancreas (8) was hybridized with a perlecan-specific probe and washed stringently. The bottom panel shows a control hybridization with a β-actin-specific probe to indicate differences in total mRNA content.
with other studies performed with mAbs against recombinant fragments from domain III of perlecan [24, 25], and with a polyclonal antiseraum against perlecan from the EHS-tumor [11]. However, the exact localization of perlecan in the GBM can hardly be deduced from immunofluorescence microscopy studies. Our results from immunoelectron microscopy indicate that perlecan is present in the GBM, but only on the endothelial side. Moreover, perlecan is distributed in a non-homogenous pattern and many segments of the GBM were not stained by 95J10. Therefore, charge-selective properties of the GBM cannot be ascribed to the anionic charge of perlecan alone.

The expression pattern of perlecan is in marked contrast to that observed with M215, a previously described mAb against HSPG isolated from the GBM [31]. This HSPG is less widely distributed than perlecan, as shown by indirect immunofluorescence on multiple human tissues. In the kidney, this antibody predominantly stained the GBM in a linear manner. Similar results were obtained with other monoclonal and polyclonal antibodies raised against GBM-HSPG, and with a mAb that recognizes an epitope on the HS chain [5, 8, 9]. The homogenous distribution of this HSPG within the GBM was confirmed by immunoelectron microscopy.

Our results indicate that two immunologically unrelated HSPG species are present in the GBM. This conclusion is based on the following considerations. Firstly, the anti-HSPG antibodies 95J10 and M215 show a clearly different distribution in human tissues. Comparing the staining patterns of 95J10 and M215, it is of importance that both antibodies are directed against the core proteins. The exact composition of the glycosaminoglycan residues is not solely dependent on the nature of the core protein, but is also influenced by the cellular environment in which they are synthesized and modified. Secondly, we demonstrated that a polyclonal antiseraum against GBM-HSPG does not cross-react with perlecan. Thirdly, observations from other groups also support the presence of multiple extracellular HSPG species in the glomerulus. In one of these investigations, proteoglycan synthesis was studied in cultures of three cell types derived from calf glomeruli. Epithelial cells excreted immunologically distinct HSPG components (approximately 300 kDa) as compared to endothelial and mesangial cells, which produced a perlecan-like HSPG (molecular mass 500 kDa) [35]. Another study supported the synthesis of perlecan-like HSPG by cultured rat mesangial cells [36]. Finally, partial amino acid sequences of HSPG isolated from bovine and human kidney also supported the presence of HSPG species that are unrelated to perlecan [37, 38].

After hybridization of kidney mRNA, only the full-length perlecan transcript could be distinguished (Fig. 7). Although minor differences in mRNA length cannot be detected by this method, such small rearrangements could not explain the altered immunoreactivity towards mAbs with different domain specificities (this study and [24, 25]). Heparan-sulfate-carrying splice isoforms of perlecan could not be missed through the choice of the probe, because the corresponding exon is required for the presence of HS chains [20]. Therefore, the production of multiple HSPGs in the GBM is not mediated by alternative splicing of perlecan. This indicates that a different gene is involved.

The availability of the recombinant perlecan-(24–404)-peptide and mAb 95J10 could be of value in determining the functional properties of the individual domains of the perlecan core protein. The ultrastructural localization of perlecan in the GBM suggests that its role in the maintenance of selective glomerular permeability is more modest than was initially assumed. The presence of an additional HSPG, which is unrelated to perlecan, may open a new direction for investigating the structural basis of charge-selective GBM permeability. The unidentified HSPG that is highly expressed in the GBM may play an important role in renal function.

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