Hydroxyl Radicals Depolymerize Glomerular Heparan Sulfate in Vitro and in Experimental Nephrotic Syndrome*

(Received for publication, July 10, 1997, and in revised form, August 6, 1997)

From the Division of Nephrology, University Hospital St. Radboud, 6500 HB Nijmegen, The Netherlands

C. J. I. Raats†, M. A. H. Bakker, J. van den Born, and J. H. M. Berden

Heparan sulfate, the polysaccharide side chain of heparan sulfate proteoglycan, is important for the permselective properties of the glomerular basement membrane. In this report, we show a role for hydroxyl radicals in heparan sulfate degradation and an enhanced glomerular basement membrane permeability. First, in enzyme-linked immunosorbent assay, exposure of coated heparan sulfate (proteoglycan) to reactive oxygen species resulted in a ±50% decrease of binding of a monoclonal antibody against heparan sulfate, whereas binding of an antibody against the core protein remained unaltered. Second, on polyacrylamide gel electrophoresis, the molecular weight of heparan sulfate exposed to radicals was reduced which indicates depolymerization. Both in enzyme-linked immunosorbent assay and gel electrophoresis, hydroxyl radicals are instrumental for heparan sulfate degradation as shown by the addition of various radical scavengers. Third, in an experimental model for human nephrotic syndrome (Adriamycin nephropathy in rats), glomerular basement membrane staining of two recently described anti-heparan sulfate antibodies (JM403 and KJ865) was reduced by 24 and 43%. Treatment of Adriamycin-exposed rats with the hydroxyl radical scavenger dimethylthiourea both reduced albuminuria by 37% (p < 0.01) and partly prevented loss of heparan sulfate staining by 53% (JM403) and 39% (KJ865) (p < 0.03). In contrast to the heparan sulfate side chains, the core protein expression and the extent of glycanation did not change in Adriamycin nephropathy. We conclude that glomerular basement membrane heparan sulfate is susceptible to depolymerization by hydroxyl radicals leading to loss of glomerular basement membrane integrity and albuminuria.

Heparan sulfate (HS)† is the anionic polysaccharide side chain of heparan sulfate proteoglycan (HSPG) present in basement membranes, extracellular matrix, and on the cell surface of many (if not all) cell types (1–3). Several investigators have shown that HS plays an important role in the permselective properties of the glomerular basement membrane (GBM) (4, 5).

Enzymatic digestion of HS by heparitinase resulted in an increased passage of native ferritin and albumin through the GBM (6, 7). Furthermore, intravenous injection of a monoclonal antibody (mAb) directed against HS induces acute, selective proteinuria in rats (8). A reduction in GBM HS-associated anionic sites was found with cationic probes in several human and experimental proteinuric glomerulopathies (9, 10). With recently developed antibodies directed against GBM HSPG core protein and the HS side chain (11, 12), we demonstrated a decrease in HS staining in the GBM in different human proteinuric glomerulopathies, whereas the staining of the HSPG core protein remained unaltered (13). The mechanism responsible for this observation remains to be elucidated. In lupus nephritis, masking of HS by autoantibodies complexed to nucleosomes is proposed as a mechanism for the decrease in HS staining and albuminuria (14). In human and experimental diabetic nephropathy, it was suggested that the decrease in HS staining was due to loss of HS from the GBM (15, 16). These mechanisms, however, are not likely to occur in other glomerular diseases (13).

Previous reports have shown that reactive oxygen species (ROS) are able to degrade proteoglycan core proteins (17, 18) and glycosaminoglycans including HS and heparin (19–23) or can inhibit de novo synthesis of proteoglycans (17, 24). Furthermore, ROS were demonstrated to be involved in experimental glomerulopathies such as Adriamycin (ADR) nephropathy (25), puromycin aminonucleoside nephrosis (26), passive Heymann nephritis (27), and anti-GBM nephritis (28). ROS have been shown to cause proteinuria (29, 30) and loss of HS in the isolated perfused kidney model (29).

These data suggest that loss of GBM HS staining in various types of human glomerulopathies (13) might be secondary to the local production of ROS. To this end, we performed in vitro and in vivo experiments to evaluate the effects of ROS on GBM HSPG and HS and on GBM permeability. As major tools we used a set of four antibodies directed against various epitopes of HS(PG) as follows: JM403 (12) and KJ865 (31) which are directed against different domains in the HS side chain of HSPG, 3G10 which is directed against an epitope of HS that is increased passage of native ferritin and albumin through the GBM (6, 7). Furthermore, intravenous injection of a monoclonal antibody (mAb) directed against HS induces acute, selective proteinuria in rats (8). A reduction in GBM HS-associated anionic sites was found with cationic probes in several human and experimental proteinuric glomerulopathies (9, 10). With recently developed antibodies directed against GBM HSPG core protein and the HS side chain (11, 12), we demonstrated a decrease in HS staining in the GBM in different human proteinuric glomerulopathies, whereas the staining of the HSPG core protein remained unaltered (13). The mechanism responsible for this observation remains to be elucidated. In lupus nephritis, masking of HS by autoantibodies complexed to nucleosomes is proposed as a mechanism for the decrease in HS staining and albuminuria (14). In human and experimental diabetic nephropathy, it was suggested that the decrease in HS staining was due to loss of HS from the GBM (15, 16). These mechanisms, however, are not likely to occur in other glomerular diseases (13).

Previous reports have shown that reactive oxygen species (ROS) are able to degrade proteoglycan core proteins (17, 18) and glycosaminoglycans including HS and heparin (19–23) or can inhibit de novo synthesis of proteoglycans (17, 24). Furthermore, ROS were demonstrated to be involved in experimental glomerulopathies such as Adriamycin (ADR) nephropathy (25), puromycin aminonucleoside nephrosis (26), passive Heymann nephritis (27), and anti-GBM nephritis (28). ROS have been shown to cause proteinuria (29, 30) and loss of HS in the isolated perfused kidney model (29).

These data suggest that loss of GBM HS staining in various types of human glomerulopathies (13) might be secondary to the local production of ROS. To this end, we performed in vitro and in vivo experiments to evaluate the effects of ROS on GBM HSPG and HS and on GBM permeability. As major tools we used a set of four antibodies directed against various epitopes of HS(PG) as follows: JM403 (12) and KJ865 (31) which are directed against different domains in the HS side chain of HSPG, 3G10 which is directed against an epitope of HS that is generated by digestion of HSPG with heparitinase (32), and BS13 which is directed against the HSPG core protein (33). In enzyme-linked immunosorbent assay (ELISA), we studied the effects of ROS on immobilized HS from bovine kidney or HSPG isolated from rat GBM. On polyacrylamide gel electrophoresis (PAGE), we evaluated the effect of ROS on the molecular weight of HS. Identification of the radical(s) primarily involved in HS alteration was performed by the use of specific oxygen radical scavengers. To investigate the physiological significance of ROS on GBM HSPG expression and GBM permeability, we evaluated HS alterations in the nephrotic syndrome in rats after intravenous injection of ADR (doxorubicin, a member

* This study was supported by Grant CB93.1318 from the Dutch Kidney Foundation. The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked "advertisement" in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.
† To whom correspondence should be addressed: Division of Nephrology, University Hospital St. Radboud, P.O. Box 9105, 6500 HB Nijmegen, The Netherlands. Tel.: 31-24-3616539; Fax: 31-24-3540022; E-mail: C.Raats@nefro.azn.nl.
‡ The abbreviations used are: HS, heparan sulfate; HSPG, heparan sulfate proteoglycan; GBM, glomerular basement membrane; mAb, monoclonal antibody; ROS, reactive oxygen species; ADR, Adriamycin; ELISA, enzyme-linked immunosorbent assay; PAGE, polyacrylamide gel electrophoresis; PBS, phosphate-buffered saline; ID, hypoxanthine; XO, xanthine oxidase; SOD, superoxide dismutase; DMTU, dimethylthiourea; DPO, deferoxamine; IP, immunofluorescence; BW, body weight; AU, arbitrary units; FITC, fluorescein isothiocyanate; ANOVA, analysis of variance.

26734
of the anthracycin family), since in this model the generation of ROS has been shown (25, 34). The impact of ROS on GBM HSPG and HS expression and albuminuria in this model was investigated by intervention studies with radical scavengers. Our results indicate that hydroxyl radicals are important for both GBM HS degradation and increased GBM permeability in ADR nephropathy in rats.

MATERIALS AND METHODS

In Vitro Generation of ROS

To study the effect of ROS on HS in vitro, ROS were generated via the hypoxanthine-xanthine oxidase system and the iron-catalyzed Haber-Weiss reaction according to the method described by Moseley et al. (19).

In this system, \( \mathrm{O}_2^\cdot \), \( \mathrm{H}_2\mathrm{O}_2 \), and \( \cdot \mathrm{OH} \) are formed as is indicated by the following Equations 1-4.

\[
\begin{align*}
\text{Hypoxanthine oxidase} & \rightarrow \text{xanthine} + \text{uric acid} + \mathrm{O}_2 \\
20 \mathrm{O}_2 + 2\mathrm{H}^\cdot & \rightarrow \mathrm{H}_2\mathrm{O}_2 + \mathrm{O}_2 \\
\mathrm{Fe}^{3+} + \mathrm{O}_2 & \rightarrow \mathrm{Fe}^{2+} + \mathrm{O}_2 \\
\mathrm{Fe}^{3+} + \mathrm{H}_2\mathrm{O}_2 & \rightarrow \cdot \mathrm{OH} + \cdot \mathrm{OH} + \mathrm{Fe}^{2+}
\end{align*}
\]

(Eq. 1)

(Eq. 2)

(Eq. 3)

(Eq. 4)

In Vitro Generation of ROS

Hypoxanthine (HX, Sigma) and xanthine oxidase (XO, Sigma, grade III from buttermilk) were dissolved in a buffer containing 50 mM \( \text{K}_2\text{HPO}_4 \), pH 7.8, 1 mM EDTA, and (unless stated otherwise) 55 mM \( \text{Fe}^{3+}\)-EDTA chelate and incubated in the wells of an HS-coated micro titer plate for 2 h at 37 °C in the presence or absence of various concentrations of superoxide dismutase (SOD, EC 1.15.1.1 from bovine erythrocytes, Sigma; concentration range from 0.15-2600 units/ml), dimethylthioura (DMTU, Sigma; from 0.003 to 50 mg/ml), or deferoxamine (DFO, Ciba-Geigy AG, Basel, Switzerland; from 0.003 to 50 mg/ml). HS was also exposed to IX and XO in an iron-free buffer. The ELISA was performed as described below. For PAGE, HX and XO were incubated with \( 20 \mu \)g of HS for 2 h at 37 °C in the presence or absence of either 0.25 units/ml SOD, 1 mg/ml DMTU, or 12.5 mg/ml DFO. HS was also exposed to HX and XO in an iron-free buffer. Then, the sample was boiled for 5 min to inactivate XO, centrifuged for 10 min at 13,000 rpm, and loaded on a polyacrylamide gradient gel (35).

Antibodies

For ELISA and immunofluorescence (IF) (see below), we used various antibodies directed against different epitopes of HS/PG as follows: two mAbs that recognize different epitopes in the HS chain, mouse mAb JM403 which is directed against low-sulfated domains of HS containing an N-unsubstituted glucosamine unit (6, 12), and mouse mAb KJ865 which is directed against N-acetylated domains of HS (31); goat polyclonal antibody BL31 which is directed against the core region of HSPG (33) and mouse mAb 3G10 which recognizes HS stubs generated by heparitinase digestion (32). By this treatment, a terminal 4,5-unsaturated uronate residue is formed that is essential for recognition by 3G10. The staining by 3G10 can serve as a general HS marker, independent of the extent of HS modification. Fig. 1 shows schematically the general structure of an HSPG molecule and the binding sites of the four antibodies used in this study.

ELISA

HS (from bovine kidney; Seikagaku Kogyo, Tokyo, Japan) was coated to a poly styrene flat-bottom microtiter plate (NUNC Maxisorp; Life Technologies, Inc., Breda, The Netherlands) in a concentration of 50 \( \mu \)g/ml in phosphate-buffered saline (PBS), 100 \( \mu \)l/well, overnight at room temperature. Alternatively, HSPG, isolated from rat GBM as described earlier (31), was coated 1 \( \mu \)g/ml in PBS, 100 \( \mu \)l/well, overnight at room temperature. After washing 6 times with PBS, HX and XO were added in an end volume of 100 \( \mu \)l/well for 2 h at 37 °C. Thereafter, the plates were washed 6 times with PBS and incubated with 1% gelatine (Difco) in PBS, 150 \( \mu \)l/well, for 2 h at room temperature to prevent nonspecific binding. After washing 6 times with PBS containing 0.05% Tween 20 (PBS/Tween), the wells were incubated with anti-HS side chain mAb JM403 1:50,000 or anti-HSPG core protein antibody BL31 1:2,000 in PBS/Tween, 100 \( \mu \)l/well, for 1 h at room temperature. Thereafter, the wells were washed 6 times with PBS/Tween and incubated with either 100 \( \mu \)l of peroxidase-labeled rat anti-mouse Ig (light chain type kappa) (RM19; Central Laboratory for Blood Transfusion, Amsterdam, The Netherlands) 1:1,600 in PBS/Tween or with peroxidase-labeled rabbit anti-goat Ig (Dakopatts, Glostrup, Denmark) 1:2,000 in PBS/Tween for 1 h at room temperature. Then, the wells were washed 9 times with PBS/Tween and incubated with 100 \( \mu \)l of tetramethylbenzidine substrate solution that was prepared immediately before use (SFRi Laboratories, Berganton, France). After 20 min, the reaction was stopped with 2 M \( \text{H}_2\text{SO}_4 \), and absorption was measured at a wavelength of 450 nm using a Bio-Rad Multilabel Reader.

Animals

For all experiments, we used male Wistar-Unilever rats that were bred at our animal laboratory and weighed 150-200 g at the start of the experiments. The animals were fed standard food and tap water ad libitum.

Experimental Design

Time Response Study — In a previous study (36), we compared different doses of ADR. We found that a dose of 5 mg/kg body weight (BW) Adriamycin® (Adriablastina; Farmitalia, Milan, Italy) is optimal to induce proteinuria. To study the time course of ADR nephropathy, 40 animals were injected with 5 mg of ADR/kg BW and after either 1-5 weeks 8 rats were sacrificed, and their kidneys were snap-frozen in liquid nitrogen and used for IF. Urine and serum samples were col-
Effect of ROS on HS and HSPG in vitro. Coated HS (A, B, and C) or HSPG from rat GBM (D, E, and F) were incubated with hypoxanthine and xanthine oxidase for 2 h at 37 °C in the presence of various concentrations of superoxide dismutase (A and D), dimethylthiourea (B and E), or deferoxamine (C and F). Then ELISA was performed with anti-HS mAb JM403 (A–F, ●) and anti-HSPG core protein antibody BL31 (D–F, ▲).

Treatment with ROS Scavengers — To study the involvement of ROS in ADR nephropathy, 22 rats received an injection of 5 mg of ADR/kg BW and were treated with ROS scavengers. One group (n = 8) received an initial intraperitoneal injection of 500 mg of DMTU/kg BW dissolved immediately before use in saline 6 h before the ADR injection, followed by intraperitoneal injections of 125 mg of DMTU/kg BW twice daily (at 8.00 and 20.00 h) for 7 days, starting 6 h after ADR injection. The other 2 groups (both n = 7) received either 52,600 units of SOD/kg BW dissolved immediately before use in saline or the same volume of saline intraperitoneally twice daily (at 8.00 h and 20.00 h) for 7 days starting 6 h before ADR injection. These doses are in accordance with other studies, where they were found to be effective (26, 37–39).

Urine was collected every week to determine albumin and IgG concentrations. Clearance of albumin was calculated as urine albumin excretion per 24 h/serum albumin concentration, and selectivity index was calculated as clearance IgG/clearance albumin.

Determination of Urine and Serum Albumin and IgG Concentration

Urinary albumin excretion was measured in urine collected for 24 h in metabolic cages. Urine and serum concentrations of albumin were determined by rocket immunoelectrophoresis (40), with goat anti-rat albumin and rat albumin as a standard (both from Nordic, Tilburg, The Netherlands). Urine and serum IgG concentrations were determined by ELISA (8).
Assessment of HS and HSPG Staining in the GBM by Indirect IF

Indirect IF was performed as described previously (11, 13) on 2-μm cryostat sections of rat kidneys that were fixed during 10 min in acetone at 4 °C (except for the sections that were digested by heparitinase to allow staining with 3G10). All antibodies were diluted in PBS containing 1% BSA and 0.1% sodium azide (IF buffer) and were incubated for 45 min at room temperature. Sections were incubated with mAb KJ865 diluted 1:20, followed by FITC-labeled goat anti-mouse IgG Fc-specific (Nordic, Tilburg, The Netherlands), diluted 1:500 in IF buffer containing 4% normal rat serum. To evaluate the GBM staining with a mAb directed against an epitope of HS that is generated by digestion with heparitinase, non-fixed sections were incubated for 1 h at 37 °C with 0.25 units/ml heparitinase (heparin-sulfate lyase, EC 4.2.2.8, Sigma) in 50 mM HEPES and 10 mM CaCl2, pH 7.0. Next, the sections were incubated with mAb 3G10 diluted 1:200 in IF buffer, followed by incubation with FITC-labeled goat anti-mouse IgG2b (Southern, Birmingham, AL) diluted 1:100 in IF buffer containing 5% normal rat serum. Sections were double-stained with goat anti-human GBM HSPG core protein BL31 and mouse anti-rat GBM Hs mAb JM403. Sequential incubations were performed as follows: 1) goat anti-HSPG core protein BL31, diluted 1:400; 2) FITC-labeled rabbit anti-goat IgG (De Beer Medicals, Diessen, The Netherlands), diluted 1:500 in IF buffer containing 4% normal rat serum; 3) mouse anti-HS mAb JM403, diluted 1:800; 4) TRITC-labeled goat anti-mouse IgM Fc-specific (Nordic, Tilburg, The Netherlands), diluted 1:250 in IF buffer containing 4% normal rat serum. The double staining experiments included the following controls: 1) omitting BL31 or JM403 or both; 2) incubating BL31 or JM403 with the conjugate used for the detection of the other antibody in the double staining. After incubation with antibodies the sections were washed with PBS and embedded in Vectashield mounting medium H-1000 (Vector Laboratories Inc., Burlingame, CA) and examined with a Zeiss Axioskop microscope equipped with an epi-illuminator. The staining intensities of the antibodies in the GBM were scored in 25 glomeruli on a scale between 0 and 10. No GBM staining was given a score of 0, and 10% of the antibodies in the double staining.

Controls: 1) omitting BL31 or JM403 or both; 2) incubating BL31 or JM403 with the conjugate used for the detection of the other antibody in the double staining.

After incubation with antibodies the sections were washed with PBS and embedded in Vectashield mounting medium H-1000 (Vector Laboratories Inc., Burlingame, CA) and examined with a Zeiss Axioskop microscope equipped with an epi-illuminator. The staining intensities of the antibodies in the GBM were scored in 25 glomeruli on a scale between 0 and 10. No GBM staining was given a score of 0, and 10% of the antibodies in the double staining.

Controls: 1) omitting BL31 or JM403 or both; 2) incubating BL31 or JM403 with the conjugate used for the detection of the other antibody in the double staining.

Results of the double staining were evaluated on a scale from 0 to 10, with 0 representing no staining and 10 full staining. For statistical analysis, the Mann-Whitney U test and the ANOVA test were used for inter-group comparisons. To test correlations, the Spearman rank correlation test was used. A p value of less than 0.05 was considered significant.

Statistical Analysis

For statistical analysis, the Mann-Whitney U test and the ANOVA test were used for inter-group comparisons. To test correlations, the Spearman rank correlation test was used. A p value of less than 0.05 was considered significant.

Results

Effect of ROS on HS(PG) in Vitro—To find optimal concentrations of HX and XO, concentration ranges from 0.002 to 7.36 mM HX and from 0.01 to 50.4 milliunits/ml XO were tested on coated HS in ELISA (Fig. 2). The optimal concentrations of HX and XO were chosen such that both components alone had no effect on the ELISA signal, and the combination resulted in a maximal decrease of JM403 signal on coated HS. The optimal concentrations were 1.84 mM HX and 12.6 milliunits/ml XO, resulting in a decrease of ELISA signal of JM403 of 58 ± 5%. These concentrations (1:4 dilution in Fig. 2) were used for all further experiments.

The addition of SOD to the HX and XO mixture dose-dependently prevented loss of the anti-HS signal in ELISA (Fig. 3A). Since SOD inactivates O2−, the first oxygen radical formed in the cascade of reactions, no additional ROS (H2O2 and •OH) will be formed. This indicates that ROS are indeed responsible for the decrease in HS recognition by mAb JM403. This experiment, however, does not answer the question which of the radicals is primarily responsible. Therefore, we also added DMTU to HX-XO. Now, O2− and H2O2 are still formed, but •OH radicals are scavenged. DMTU also dose-dependently prevented loss of the anti-HS signal in ELISA (Fig. 3B). This was corroborated by the finding that chelation of Fe3+ by DFO (Fig. 3C), thus anticipating the formation of •OH radicals by the

Theoretically, two different mechanisms might explain this finding. First, •OH radicals alter the biochemical composition of HS, thereby changing the epitopes recognized by mAb JM403. Second, •OH radicals depolymerize HS chains into oligosaccharides. Therefore, we evaluated the molecular size of native and ROS-exposed HS (from bovine kidney) on PAGE. In addition, HS was exposed to ROS in the presence of various scavengers. On PAGE, native HS forms a band in the top of the gel (Fig. 4, lane 1), corresponding to a molecular weight of approximately 200 kDa. This band is absent in both ROS-exposed HS (from bovine kidney) on PAGE. In addition, HS was exposed to ROS in the presence of various scavengers. On PAGE, native HS forms a band in the top of the gel (Fig. 4, lane 1), corresponding to a molecular weight of approximately 200 kDa. This band is absent in both ROS-exposed HS (from bovine kidney) on PAGE. In addition, HS was exposed to ROS in the presence of various scavengers.
Hydroxyl Radicals Depolymerize Glomerular Heparan Sulfate

...after incubation with 1.84 mM HX and 12.6 milli-units/ml XO, this pattern changes to a smear down to the level of the octasaccharides, indicating depolymerization of HS (lane 7). Adding either DMTU, SOD, or DFO to HX-XO or incubating HX-XO in an iron-free buffer prevented the reduction in molecular mass (lanes 8–11). HX or XO alone had no effect on HS (lanes 5 and 6). From this experiment, we conclude that ‘OH radicals depolymerize HS into oligosaccharides.

In Vivo Experiments—These results (degradation of HS but no effect on the core protein of HSPG) resembled our IF finding in various human glomerular diseases (13). To investigate an possible role of ROS in vivo, we decided to induce a nephrotic syndrome into rats by intravenous injection of ADR, since ROS have been suggested to play a role in this disease.

Time Response Study—The characteristics of ADR nephropathy are shown in Table 1. The injection of 5 mg/kg BW ADR induced a heavy albuminuria and a decrease in serum albumin levels. The induced proteinuria was selective, since the selectivity index (clearance of IgG/clearance of albumin) was 0.17 ± 0.06 at week 4 (versus 0.68 ± 0.32 at week 0, p < 0.001). This indicates a preferential urinary loss of albumin, which might be due to loss of negative charges (i.e. HS) from the GBM.

We then analyzed the expression of HS(PG) in the GBM after ADR injection. The antibodies directed against the HSPG core protein, the HS side chain, and the HS stub generated by heparitinase stain the GBM in normal rat kidney sections in a bright linear pattern as shown in Fig. 5, A–D. In ADR-treated rats, we did not observe a change in the staining for the HSPG core protein and HS stubs (Fig. 5, E and H). In contrast to this, the GBM staining with anti-HS mAbs JM403 and KJ865 at week 4 decreased to 76 and 57%, respectively, of the pretreatment value (both: p < 0.001; Fig. 5, F and G). This decrease did not occur uniformly but focally and segmentally in the glomeruli. To analyze a possible relationship between the development of albuminuria and HS loss, we investigated the effect of these ROS scavengers on the GBM staining of HS with mAbs JM403 and KJ865 for the scavenger-treated groups are higher GBM staining for JM403 and KJ865 (Fig. 5, F and G). These findings indicate a normal expression of the HSPG core protein as well as an unaltered staining of HS leading to a decreased recognition by a specific anti-HS mAb in ELISA. PAGE revealed that HS was depolymerized by ROS. Addition of specific scavengers of hydroxyl radicals prevented this depolymerization both in ELISA and in PAGE. This indicates that hydroxyl radicals are responsible for this effect. Other investigators have also shown that ROS can cause depolymerization of glycosaminoglycans (19–23). Most studies focused on hyaluronic acid and heparin which are indeed depolymerized by ROS (21–23, 42–44), but little is known about the susceptibility of HS to ROS.

We observed in ADR nephropathy a progressive albuminuria that was accompanied by an increase in selectivity, compatible with the loss of negative charges from the GBM. The number of HSPG core molecules and HS side chains was unaltered, but there was a decrease of the GBM staining by two anti-HS mAbs which recognize different domains in the HS side chain. In addition, this loss of HS staining correlated with albuminuria. Treatment with the hydroxyl radical scavenger DMTU resulted in an amelioration of albuminuria and a partial prevention of the loss in GBM HS staining. This is in line with our in vitro findings that hydroxyl radicals can induce depolymerization of HS. On the basis of these results, we postulate that the ensuing albuminuria is (at least partly) due to the depolymerization of HS, leading to loss of HS from the GBM. In various human and experimental proteinuric glomerulopathies, loss of HS staining in the GBM has been observed as well (13–15, 45). Moreover, the correlation between albuminuria and loss of HS staining is not unique for ADR nephropathy, since we found a similar correlation in murine lupus nephritis (14), active Heymann nephritis (45), and in patients with diabetic nephropathy (15). This suggests that, besides other postulated mechanisms (14–16), depolymerization of GBM HS by ROS could play a role in other glomerulopathies as well. This is substantiated by the beneficial effects of ROS scavengers, not only in ADR nephropathy (34, 39) but also in various other experimental models of glomerulopathy (46), such as purine aminonucleoside nephrosis (26), passive Heymann nephritis, (27) and anti-GBM nephritis (28). Therefore, depolymerization of HS by ROS could be a common mechanism responsible for HS loss and proteinuria in these diseases.

In contrast to DMTU, SOD had no effect on albuminuria and HS staining in our hands. Data on the anti-proteinuric effect of SOD in ADR nephropathy in the literature are conflicting. Okasora et al. (47) reported a beneficial effect, whereas Bertolatus et al. (34) found no protection, even with SOD conjugated to polyethylene glycol, which has been shown to enhance the effects of SOD by prolonging its half-life (48, 49). The finding that SOD was not effective may be a consequence of the relatively large dimensions of the enzyme which prevent easy passage across the cell membrane (50).

Apart from degradation of HS, ROS could also exert a direct toxic effect on the glomerular epithelial cell resulting, for example, in a structurally altered HS. Indeed, an increase in the extent of sulfation of HS could be an alternative explanation for the decrease in GBM HS staining that we found. Both anti-HS mAbs that we used in our study recognize exclusively low- or non-sulfated domains in the HS side chain. mAb JM403 is directed against a low-sulfated domain of HS containing an N-unsubstituted glucosamine unit (12), whereas mAb KJ865 is directed against N-acetylated domains of HS (31). Increase of HS sulfation greatly diminishes recognition by both mAbs and thus might explain loss of GBM staining. HS oversulfation,
Fig. 5. GBM HSPG staining of normal rats or rats with ADR nephropathy treated either with saline or dimethylthiourea. Indirect IF on kidney sections of normal rats (A-D), saline-treated ADR rats (E-H), or dimethylthiourea-treated ADR rats (I-L) with antibodies directed against the following epitopes of HSPG: A, E, and I, HSPG core protein BL31; B, F, and J, anti-HS mAb JM403 in a double staining; C, G, and K, anti-HS mAb KJ865; D, H, and L, heparitinase-created HS-stub (mAb 3G10) (magnification: 150 ×).
Hydroxyl Radicals Depolymerize Glomerular Heparan Sulfate

Fig. 6. A, time course of GBM HS staining in ADR nephropathy. Rats received a single intravenous injection of 5 mg/kg ADR at week 0. GBM HS staining was evaluated in indirect IF with anti-HS mAb JM403. Maximal score is 250 arbitrary units. B, correlation between albuminuria and GBM HS staining in ADR nephropathy.

However, seems not very likely, since it is difficult to correlate this to an increased GBM permeability. This hypothesis is contradicted as well by the loss of anionic sites that were found in ADR nephropathy (51). Moreover, our in vitro data convincingly show the susceptibility of GBM HS to degradation by ROS. In a related model, however, puromycin aminonucleoside nephrosis, a higher [35S]sulfate incorporation into glomerular HS was found (suggesting over sulfation of glomerular HS) (52).

What could be the physiological meaning of HS susceptibility to ROS? GBM HS contains large N-acetylated stretches (recognized by KJ865), which are very sensitive to ROS (23). This could mean that HS functions as an antioxidant in the GBM, such that other molecules are protected from degradation by ROS. This antioxidant effect has also been shown for heparin and hyaluronic acid (42, 43, 53). One can only speculate on the physiological effects of the (by depolymerization) released HS oligosaccharides. It is known that HS can function as an anchorage molecule for growth factors, such as basic fibroblast growth factor (54). After degradation of HS, these growth factors would be set free and activate glomerular epithelial and/or mesangial cells. Released HS oligosaccharides could also exert a local impact on the coagulation, whereas in the GBM loss of HS could lead to clogging (55).

Our present study provides evidence that ROS-mediated HS depolymerization plays a role in ADR nephropathy and is correlated to GBM permeability. Since HS interacts with other basement membrane components, such as collagen IV and laminin, it is an important factor in the assembly and integrity of basement membranes and is consequently a determinant for the charge- as well as for the size-dependent permeability (55–57). Since ROS are generated by various mechanisms in proteinuric glomerular diseases, it is probable that this mechanism is operative in different glomerulopathies resulting in an increased permeability to macromolecules.

Acknowledgments—The expert technical assistance of the biotechnicians of the Central Animal Laboratory is gratefully acknowledged.

REFERENCES