Demonstration of a Keratan Sulfate–Containing Proteoglycan in Atherosclerotic Aorta

Robert A. Robbins, William D. Wagner, Thomas C. Register, and Bruce Caterson

Proteoglycans were isolated from either grossly normal or atherosclerotic pigeon aortas after extraction with 4 M guanidinium hydrochloride and purification by ion-exchange and size-exclusion chromatography. The small-size proteoglycans (Km, 0.4, on Sepharose CL-4B) from both normal and atherosclerotic tissue contained primarily a dermatan sulfate proteoglycan with an intact molecular size of 220–330 kd and a 45-kd core protein. In addition to the dermatan sulfate proteoglycan, the preparation contained a proteoglycan recognized by monoclonal antibody (MAb) 5-D-4, indicating the presence of sulfated poly-N-acetyllactosamine sequences common to corneal and cartilage keratan sulfate. Electrophoresis on sodium dodecyl sulfate–polyacrylamide gel revealed a polydisperse proteoglycan of 60–150 kd that was recognized by MAb 5-D-4. Significantly greater immunoreactivity with MAb 5-D-4 was observed for atherosclerotic compared with normal artery. After endo-β-D-galactosidase treatment of the proteoglycan from atherosclerotic aorta, diminished MAb 5-D-4 reactivity observed by both Western blot analysis and enzyme-linked immunosorbent assay demonstrated that the material was keratan sulfate. Endo-β-D-galactosidase treatment of the intact proteoglycan generated core proteins of 28 and 38 kd. These studies suggest the presence of one or more keratan sulfate proteoglycans in grossly normal and atherosclerotic arteries. Immunochemical data suggest that sulfation of the keratan sulfate proteoglycan may be greater in atherosclerotic aorta. (Arteriosclerosis and Thrombosis 1992;12:83–91)
protein adjacent to the hyaluronic acid–binding region. The KS chains consist of repeating N-acetyllactosamine (Galβ1-4GalNAc) disaccharides, which may be sulfated at the C-6 position of either galactose or N-acetylgalactosamine.

Recently, anti-KS antibodies, which recognize highly sulfated regions of the KS chain, have been used to localize the PG in chondrocyte cultures, in normal and pathological muscle, in human serum, in human synovial fluid, and in other tissues from several different species including humans, chickens, cows, monkeys, rats, fish, and pigeons. Although these reports have demonstrated KS-containing PGs in a variety of tissues other than cornea and cartilage, few studies have described the isolation and structural properties of these molecules. In the present study, we present the immunochromatographic and biochemical characterization of KS-PGs isolated from grossly normal and atherosclerotic arteries of the White Carneau pigeon. The findings suggest that the KS-PG is discrete from the large CS-PG-containing KS chains in artery and that the sulfation of the KS-PG is enhanced in atherosclerotic tissue.

Methods

Materials

Ultrapure guanidine hydrochloride (GdnHCl) and urea were purchased from Schwartz-Mann (Cleveland, Ohio); Coomassie blue RR 250, 6-aminohecanoic acid, Alcian blue, x-ray film (X-omat AR), and cellulose-coated plastic thin-layer chromatography plates from Eastman Kodak Co. (Rochester, N.Y.); and N,N-methylene-bis-acrylamide, sodium dodecyl sulfate (SDS), 4-chloro-l-naphthol, and acrylamide from Bio-Rad (Richmond, Calif.). Chondroitinase ABC (from Proteus vulgaris) and keratanase (from Pseudomonas sp.) were obtained from Seikagaku America, Inc. (St. Petersburg, Fla.). Trypsin (diphenylcarbamyl chloride–treated, type XI), phenylmethylsulfonyl fluoride (PMSF), and peptatin were obtained from Sigma Chemical Co. (St. Louis, Mo.). Endo-β-D-galactosidase (from Escherichia freundia) was from V-Labs, Inc. (Covington, La.). Horseradish peroxidase (HRP)–conjugated anti-mouse immunoglobulin G (IgG) was obtained from Cappel Laboratories (Cochraville, Pa.). HRP-conjugated Ig (IgG plus IgM) fraction was obtained from Southern Biotechnology (Birmingham, Ala.). Nitrice-lulose membranes (0.45 µm) were obtained from Schleicher and Schuell (Keene, N.H.). High-performance liquid-chromatography reagents were obtained from Waters Division of Millipore (Milford, Mass.). All other chemicals were reagent grade and were purchased from Fisher Scientific (Pittsburgh, Pa.).

Monoclonal Antibodies

The production and characterization of the monoclonal antibody (MAb) used in this study have been thoroughly described. In brief, the MAb 5-D-4 directed against KS recognizes a pentasulfated hexa-saccharide common to both corneal and skeletal KS and can bind KS in its native form. The MAb 2-B-6 directed against C4S or DS recognizes the terminal unsaturated disaccharide, sulfated in the C-4 position of the N-acetyltosamine residue present on the carbohydrate stub of the core protein subsequent to chondroitinase ABC treatment.

Source of Animals

Pigeons were obtained from the production colonies of the Bowman Gray School of Medicine. Pigeons were randomly bred White Carneau of either sex and ranged in age from 1 to 5 years. Of the 222 pigeons used, 138 were fed a cholesterol-free diet throughout their lives and 84 were fed a cholesterol-containing diet for 6 months. The cholesterol-containing diet consisted of pigeon pellets containing 0.5% cholesterol and 10% lard by weight. White Carneau pigeons develop naturally occurring atherosclerosis at several arterial sites, most consistently near the bifurcation of the celiac artery in the distal part of the thoracic aorta. The atherosclerotic lesions are histologically and biochemically similar to human atherosclerotic lesions. Feeding of cholesterol-containing diets has been shown to accelerate atherosclerosis in this species.

Extraction and Purification of Proteoglycans

Only the thoracic aorta extending from the inferior border of the right brachiocephalic artery to 2 mm distal to the inferior border of the branch point of the celiac artery was used in the study. The atherosclerotic lesions consisted of mixed lesions with variable amounts of smooth muscle cells, macrophages, and connective tissue. Grossly normal aortic tissue (41.9 g) and 10.2 g atherosclerotic tissue were obtained from aortas of 222 pigeons. After removal of periadventitial tissue, aortic intima–media was finely minced (1–2 mm) and extracted with 16 volumes of 4 M GdnHCl and 0.05 M sodium acetate (pH 5.8) containing 100 mM 6-aminohecanoic acid, 11.1 mM EDTA, 5 mM benzamidine hydrochloride, 2.5 mM 1,10-phenanthroline, 5.1 mM trypstatin hydrochloride, and 0.5% 3-[3-cholamidopropyl]dimethylammonio]-1-propanesulfonate (CHAPS) for 48 hours at 4°C. The filtered extracts were concentrated on Amicon YM 30 membranes and dialyzed against 7 M urea in 0.05 M Tris, pH 6.8, containing 0.5% CHAPS. PGs (including in vitro S-labeled PG from pigeon aorta as an internal marker) were fractionated on DEAE–Sephacel by an initial elution with 60 ml 7.0 M urea in 0.05 M Tris HCl (pH 6.8), followed by a continuous 100-m M NaCl gradient of 0–1 M NaCl.

Fractions containing the PG, which eluted with 0.38–0.47 M NaCl, were pooled, concentrated, and dialyzed against 4 M GdnHCl containing protease inhibitors. The PG types were separated by size-exclusion chromatography on a column of Sepharose CL-4B, with 4.0 M GdnHCl, 0.05 M sodium acetate (pH 5.8) containing 0.5% CHAPS, and protease inhibitors as the eluant. The PG eluted as two peaks of...
material, a large PG, eluting at the $V_0$ and a small population of PG, included with a $K_w$ of $-0.4$. Fractions corresponding to PG-I or PG-II were pooled, dialyzed against double-distilled water, and lyophilized. In previous studies of human aorta and pigeon aorta, C6S-PG was found to be the major component of large PG material and DS-PG was the major component of the small PG material. Four preparations of PG were obtained: 1) small PG from normal aorta, 2) small PG from atherosclerotic aorta, 3) large PG from normal aorta, and 4) large PG from atherosclerotic tissue. In our previous study, dot-blot immunoblotting indicated that KS was present mainly in the small PG of atherosclerotic tissue. Therefore, preparations of small PG were used in the present study.

**Enzyme Digestions**

PG preparations (1 mg/ml) were digested with chondroitinase ABC, 0.025 units/ml, in 0.1 M Tris, 0.03 M sodium acetate, and 10 mM EDTA (pH 8.0) containing 0.036 mM pepstatin, 0.5 mM PMSF, and 1.0 mM N-ethylmaleimide for 16 hours at 37°C; or with protease-free chondroitinase ABC under the same conditions excluding protease inhibitors. Digestions with endo-$\beta$-d-galactosidase (from *E. freundii*, 0.025 units/ml) were carried out in 50 mM sodium acetate, pH 5.5, for 16 hours at 37°C in the presence of the protease inhibitors mentioned previously. Digestion with keratanase (*Pseudomonas* sp., 0.025 units/ml in 0.1 M Tris acetate, pH 8.0) was carried out for 16 hours at 37°C in the presence of the protease inhibitors.

**Sodium Dodecyl Sulfate–Polyacrylamide Gel Electrophoresis (PAGE)**

Analytical polyacrylamide gradient (4–20%) SDS slab gels (160×140×1.5 mm) were formed with a 3.6% stacking gel by the method of Laemmli and Favre. SDS-PAGE electrophoresis was carried out at 200 V for 4 hours. Protein bands were detected by Coomassie blue staining, and acidic polysaccharides were detected by Alcian blue staining. The staining procedure included a first staining with Coomassie blue followed by destaining. Gels were then stained with Alcian blue followed by a repeat of the Coomassie blue staining. In some cases, samples were directly blotted to nitrocellulose after electrophoresis.

**Western Blotting**

Electrotransfer of proteins from SDS gels to nitrocellulose sheets was carried out at 4°C at 30 V overnight followed by 200 V for 3 hours in a Bio-Rad Transblot apparatus according to the method of the manufacturer. After transfer of intact PG to nitrocellulose, the epitopes recognized by MAb 2-B-6 were generated by treatment of the nitrocellulose sheet with 0.5 units chondroitinase ABC in 20 ml 0.1 M Tris acetate buffer containing 0.1% bovine serum albumin (BSA) for 1 hour at 37°C.

**Immunocharacterization**

After electrotransfer of proteins to nitrocellulose, the membrane was blocked with Tris-buffered saline (TBS), pH 7.4, containing 5% BSA and 0.5% nonfat dry milk for 1 hour at 23°C. After washing with TBS, the membranes were incubated for 2 hours at 23°C with the appropriate MAb (MAb 2-B-6 diluted 1:2,000 or MAb 5-D-4 diluted 1:2,000) in TBS containing 0.5% BSA and 0.5% nonfat dry milk. The membrane was washed three times for 15 minutes each with TBS and incubated with a secondary goat anti-mouse antibody (diluted 1:1,000 in antibody buffer) conjugated to HRP for 1 hour at 23°C. After washing six times for 10 minutes each with TBS, substrate solution (12.4 mg 4-chloro-l-naphthol in 4.15 ml methanol, 20.75 ml TBS, and 8.3 ml 30% H$_2$O$_2$) was added. The reaction was stopped with phosphate-buffered saline (PBS) containing 0.03% Na$_3$NO$_3$.

**Enzyme-Linked Immunosorbent Assay (ELISA)**

ELISA plates were irradiated for 18 hours under ultraviolet light. Each well was filled with 0.2 μg protein in 200 μl PBS–Na$_3$NO$_3$, incubated for 18 hours at 4°C, washed three times with PBS–Na$_3$NO$_3$, and blocked by treatment with PBS–Na$_3$NO$_3$ containing 0.5% BSA and 0.5% nonfat dry milk for 1 hour at 37°C. Samples were washed three times with PBS–Na$_3$NO$_3$, and incubated with a 1:2,000 dilution of MAb 5-D-4 for 2 hours at 37°C. The wells were washed six times with TBS and incubated with a 1:1,000 dilution of an HRP-conjugated goat anti-mouse IgG for 1 hour at 37°C. Then wells were washed four times with TBS and incubated for 30 minutes at 37°C in 0.1 M Tris with o-phenylenediamine substrate (20 ml o-phenylenediamine buffer containing 10 μl 30% H$_2$O$_2$), 150 μl/well. The color reaction was stopped by adding 50 μl 2 M H$_2$SO$_4$ to each well, and the plates were read at 492 nm with a Titertek Multiskan, Baxter Diagnostics, Chicago, Ill. Bovine nasal cartilage core protein prepared as a chondroitinase ABC-treated A$_4$D$_4$ fraction$^{31}$ was used as a positive control for the enzymatic action of endo-$\beta$-d-galactosidase and keratanase.

**Analytical Methods**

The hexuronic acid content of the PG preparations was determined by the method of Blumenkrantz and Asboe-Hansen, with glucuronic acid as the standard. Protein was measured according to the method of Lowry et al, with BSA as the standard.

**Results**

Preparations of small arterial PGs were enzymatically and electrophoretically characterized on a 4–20% gradient SDS-polyacrylamide gel. The reduced intact PG molecules stained with Alcian blue/Coomassie blue were identified as a polydisperse band. Intense staining was seen for both normal and atherosclerotic artery preparations at $M_1 \sim 220$–330, but staining of material was also apparent from $M_1 \sim 60$–230 (Figure 1, lanes 1 and 2). Core
proteins of the PG obtained after chondroitinase ABC treatment are shown in lanes 4 and 5. A major Coomassie blue-stained protein corresponding to 45 kd was generated, apparently from 220–330-kd material in both PG preparations. The 45-kd protein was not present in the enzyme mixture alone (lane 3). The 45-kd protein corresponds to the core protein of arterial DS-PG and is similar to preparations of pigeon and human artery DS-PG core proteins and the core protein of DS-PG in other tissues. Recent studies have demonstrated two DS-PG gene products, biglycan (DS-PG I) and decorin (DS-PG II), differing in overall molecular size but having similar-size core protein molecular weights. Further work is needed to demonstrate if the intact DS-PG material with M, 220–330 kd represents both decorin and biglycan that may not have separated effectively in this system. Material migrating at 94 kd was apparent in both preparations. This material appears to have been present in lanes 1 and 2 but in combination with polydisperse PG was not easily discernable as a discrete band.

To determine the location of the KS and/or CS chains, intact PGs were electrophoresed on a 4–20% gradient gel, transferred to nitrocellulose, then treated with chondroitinase ABC, and probed with MAb 2-B-6 and MAb 5-D-4. The majority of MAb 2-B-6 (C4S/DS) reactivity was associated with the 220–330-kd PG in both normal and atherosclerotic aorta samples (Figure 2, lanes 2 and 3). The 60–150-kd PG contained KS chains as observed by MAb 5-D-4 reactivity (Figure 2, lanes 5 and 6); no MAb 5-D-4 reactivity was associated with the 220–330-kd PG. Significantly greater immunoreactivity was observed in the intact PG preparation from atherosclerotic aorta (Figure 2, lane 6), in comparison to PG from normal artery, from which only trace immunoreactive material is presented (Figure 2, lane 5).

To further examine the GAGs and N-linked oligosaccharides associated with the two major proteins, chondroitinase ABC-generated core proteins were electrophoresed on 4–20% gradient SDS-PAGE gels, transferred to nitrocellulose, and probed with MAb 2-B-6 (Figure 3) and MAb 5-D-4 (Figure 4). In some cases, additional enzyme treatments were car-
In the present study, we have reported the presence in artery of a previously undescribed small PG reactivity, suggesting that the KS chains were not N-linked to a core protein (Figure 4, lanes 4 and 8).

The degree of susceptibility of the MAb 5-D-4–positive material to endo-β-D-galactosidase and keratanase treatment was estimated by ELISA. Endo-β-D-galactosidase treatment of the PG preparation from atherosclerotic plaque resulted in a 73% reduction in immunoreactivity compared with a 61% reduction in recognition of bovine nasal cartilage core protein used as a control. Keratanase treatment of the PG resulted in a 13% reduction in immunoreactivity. These results indicated that the immunoreactive material recognized by MAb 5-D-4 was largely a KS with variable regions of sulfation.

Because further examination of the protein associated with KS was limited by low levels in the sample, the PG preparations were radioiodinated, subjected to selective enzymatic treatments, and electrophoresed on SDS gels. The results (Figure 5) confirm the previous findings (Figure 3) that the intact 220–330-kd DS-PG from either normal artery or atherosclerotic plaque (Figure 5, lanes 1 and 2) was not affected by treatment with endo-β-D-galactosidase (Figure 5, lanes 5 and 6) but was susceptible to chondroitinase ABC treatment, generating a 45-kd core protein (Figure 5, lanes 3 and 4). After endo-β-D-galactosidase treatment of intact PG, two major proteins with approximate molecular weights of 38 and 28 kd were observed in the sample from atherosclerotic artery (Figure 5, lane 6) and appear to have been generated from intact molecules of 70–150 kd. Both proteins were also present in normal aorta (Figure 5, lane 5). The results suggest that the core proteins of the KS-PG have molecular weights of 38 and 28 kd.

Discussion

In the present study, we have reported the presence in artery of a previously undescribed small PG...
containing KS chains. Although the KS-PG was coisolated with DS-PG and an unidentified 94-kd protein, the KS-PG was shown to be distinct from these materials. There are three criteria that define the arterial PG as a KS-PG: recognition by MAb 5-D-4 and sensitivity by two different enzymes, endo-β-D-galactosidase and keratanase. Recognition by the specific MAb 5-D-4 indicated the presence of epitopes characteristic of both skeletal and nonskeletal KS. Sensitivity of the molecule to endo-β-D-galactosidase provided confirmation of the poly-N-acetyllactosamine carbohydrate composition of the molecule. Endo-β-D-galactosidase is a highly specific enzyme that requires a minimum structure of glucNAcβ(1-3)galβ(1-4)glcMVc. Degradation of the molecule with endo-β-D-galactosidase indicated that the molecule was authentic KS. The observation that treatment with keratanase produced a significantly decreased binding with MAb 5-D-4 indicated that the epitope resided in a KS chain.

Based on results of the immunoblots, the intact KS-PG migrated as polydisperse 60–150-kd material on SDS-PAGE gels, while the DS-PG had a range of 220–330 kd. After chondroitinase ABC treatment of the PG, no change was seen in the size of the KS-PG (compare Figure 2 with Figure 4). Decreases in immunoreactivity by both immunoblot and ELISA after endo-β-D-galactosidase treatment confirmed the presence of KS chains associated with the 60–150-kd PG.

Both the 45-kd core protein and the 94-kd protein possessed oligosaccharides containing 4-sulfated disaccharides because subsequent to chondroitinase ABC digestion, the proteins were recognized by MAb 2-B-6. The sizes of the 45-kd DS-PG core protein and 94-kd protein material were unaffected by endo-β-D-galactosidase treatment, demonstrating that these proteins did not contain KS chains. In atherosclerotic plaque, based on the appearance of 38- and 28-kd proteins and the loss of immunoreactivity to MAb 5-D-4 after endo-β-D-galactosidase treatment, it appears as if the PG molecules containing highly sulfated KS chains had core proteins of 38 and 28 kd. Both core proteins were also present in normal artery. The two different core proteins may represent differential processing of one KS-PG. Alternatively, based on the wide molecular weight range of material that was positive with the antibody for KS, there may be more than one type of KS-PG in the preparation, and the two proteins may represent two different KS-PGs. Funderburgh and Conrad recently described two KS-PGs isolated from bovine cornea that are comparable to the arterial KS-PG in the present study. The two corneal KS-PGs yielded core proteins of 37 kd and 25 kd after endo-β-D-galactosidase treatment. Each protein had a unique N-terminal amino acid sequence and distinct tryptic peptide map.

Several reports suggest the presence of KS-like oligosaccharides or KS chains as a component of the large, hyaluronic acid-binding CS-PG in normal human aorta and in bovine aorta. Therefore, it appears that the CS-PG of artery may be similar in structure to the large articular cartilage CS-PG in that it contains KS as well as CS chains. Recently from studies of immunoblots, we reported the presence of KS chains on pigeon arterial CS-PG. Although these studies demonstrated that KS was a component of the CS-PG, the immunolocalization of the KS in atherosclerotic lesions of the White Carneau pigeon suggested that the majority of the KS chains were localized in the intimal lesions and not coisolated with the 6-sulfated disaccharide–containing CS-PG that predominates in the normal media. Therefore, it appears that the KS-PG described in the present study is distinct from the KS on CS-PG.

A significant difference between the PG isolated from normal and atherosclerotic arteries was the increased recognition of KS-PG from atherosclerotic lesions by MAb 5-D-4. Mehmet et al showed that the smallest oligosaccharide fragment of the KS chain recognized by MAb 5-D-4 was a linear penta-sulfated hexasaccharide. The antibody has been observed to be highly specific for sulfated poly-N-acetyllactosamine sequences, with sulfation being a major factor in recognition. Recent studies of corneal KS with endo-β-D-galactosidase–generated fractions of varying sulfation suggest that the KS chain contains domains of different charge and structure at specific positions of the polysaccharide chain. The failure to completely remove the MAb 5-D-4 reactivity by endo-β-D-galactosidase results from the inability of the enzyme to cleave sulfated residues. Keratanase alone also failed to abolish recognition with MAb 5-D-4. However, KS is not hydrolyzed by keratanase when galactose is sulfated at the C-6 position.

The increased MAb 5-D-4 reactivity observed in the sample from atherosclerotic plaque indicated either increased content and/or increased sulfation of the chain. Although the results of endo-β-D-galactosidase treatment, in which a 73% loss of reactivity to MAb 5-D-4 was observed with the atherosclerotic plaque material, might seem to argue against a high degree of sulfation of the chain, we do not know the oligosaccharide sequence and sulfation pattern of the polymer.

There are a number of possibilities that may account for the presence of a highly sulfated KS-PG in atherosclerotic lesions. Alterations in the glycosylation and/or sulfation of the PG in atherosclerotic lesions may represent a modification in smooth muscle cell synthesis of PG in the changing environment of the lesion. An obvious source of factors capable of modifying smooth muscle cell metabolism are macrophages, which are known to infiltrate the artery wall during the initial stages of atherogenesis. Macrophage products such as prostaglandins, platelet-derived growth factor, and interleukin-1 have been shown to modulate PG synthesis by aortic smooth muscle cells. Thus, macrophage-derived factors may stimulate arterial smooth muscle cells to synthe-
size a highly sulfated KS-containing PG. In studies by Plaas (personal communication), mature, nondividing chondrocytes have been reported to produce fibromodulin without KS chains, whereas proliferating chondrocytes as well as chondrocytes from fetal calf cartilage produce fibromodulin with KS chains recognized by MAb 5-D-5. These studies further suggest a role for proliferating smooth muscle cells in the accumulation of KS-PG in the developing atherosclerotic lesion.

An alternative explanation for the appearance of MAb 5-D-4 reactivity in the PG from atherosclerotic artery can be drawn from observations by Scott and Haigh.59 They suggest that KS may substitute for CS in conditions of hypoxia. Aw and Jones60 have demonstrated that during hypoxia, hepatocytes reduce the production of CS precursor (uridine diphosphate [UDP]-GlC/lC from UDP-Glc and NAD), which requires oxygen and which may lead to an increase in the amount of UDP-Glc available for KS synthesis. KS biosynthesis does not require oxidation of the glucose precursor.61 Their hypothesis was based on studies of cartilage and cornea that demonstrated that KS was present in greater amounts in regions of the tissue further removed from a source of oxygen.60,62 Additionally, Balduini et al61 demonstrated that there was an inverse relation in the biosynthesis rates of KS and CS in bovine cornea.61 After inhibition of CS biosynthesis by UDP xylose, an increase in KS synthesis was observed.60 In addition to these findings, several reports suggest that hypoxic conditions may contribute to atherosclerotic lesion development.62-64 Low oxygen tension has been shown to stimulate arterial GAG synthesis in vivo64 and in cultured aortic smooth muscle cells.65 It may be possible that focal hypoxia in the atherosclerotic lesion may lead to a preferential synthesis of KS chains.

Another possibility for the increase of KS-containing PG is synthesis by macrophages, which are the major cell type present in developing atherosclerotic lesions. Human monocyte-derived macrophages and peritoneal macrophages from pigeon and guinea pig have been shown to synthesize PG in culture, primarily CS-PG,66-68 as well as oversulfated PG.69 Although the synthesis of KS-PG by macrophages has not been demonstrated to date, the environment of the atherosclerotic lesion may stimulate these cells to produce a KS-containing PG recognized by MAb 5-D-4.

As indicated, KS chains have been reported to be components of the large aortic CS-PG.10-12 and we have demonstrated MAb 5-D-4 reactivity associated with the CS-PG isolated from the atherosclerotic aorta of pigeons.7 It is possible that the 60–150-kd KS-PG results from partial degradation of the CS-PG. If the amino terminus of arterial CS-PG is rich in KS chains, it is conceivable that the KS-rich region may remain in the extracellular space after partial proteolysis of the CS-PG molecule. Plaas et al69 examined the origin of a 40–60-kd KS-PG in rabbit articular cartilage, and from pulse-chase experi-

ments, they demonstrated that the KS-PG was not derived from proteolytic processing of the large KS-containing CS-PG.

Finally, KS-PG may be derived from the plasma and become sequestered in the atherosclerotic lesion. Tho-

References

52. Watson R, Termine J, Young MF: Deduced protein sequence of bone small proteoglycan I (biglycan) shows homology with proteoglycan II (decorin) and several nonconective tissue proteins in a variety of species. J Biol Chem 1989;264:4571–4576
Robbins et al  Keratan Sulfate Proteoglycans  91

55. Scudder P, Tang POW, Hounsell EF, Lawson AM, Mehment H, Feizi T: Isolation and characterization of sulphated oligo-
saccharides released from bovine corneal keratan sulphate by
the action of endo-β-galactosidase. Eur J Biochem 1986;157:
365–373

56. Pietila K, Moilanen T, Nikkari T: Prostaglandins enhance the
synthesis of glycosaminoglycans and inhibit the growth of
rabbit aortic smooth muscle cells in culture. Artery 1980;7:
509–518

57. Burke J, Ross R: Synthesis of connective tissue macromole-
cules by smooth muscle. Int Rev Connect Tissue Res 1979;8:
119–157

58. Edwards IJ, Wagner WD, Owens RT: Macrophage secretory
products selectively stimulate dermatan sulfate proteoglycan
production in cultured arterial smooth muscle cells. Am J
Pathol 1990;136:609–621

59. Scott JE, Haigh M: Keratan sulphate: A ‘stand-in’ for chon-
droitin sulphate in conditions of oxygen lack? Biochem Soc
Trans 1987;15:1094–1095

60. Aw TR, Jones DP: Control of glucuronidation during hypoxia:
Limitation by UDP-glucose pyrophosphorylase. Biochem J
1984;214:707–712

61. Balduini C, Brovelli CA, Castellani AA: Biosynthesis of
glycosaminoglycans in bovine cornea. Biochem J 1970;120:
719–723

62. Gainer JL: Hypoxia and atherosclerosis: Re-evaluation of an
old hypothesis. Atherosclerosis 1987;68:263–266

63. Gainer JL, Chisolm GM III: Oxygen diffusion and atheroscle-

64. Helin P, Lorenzen I: Arteriosclerosis in rabbit aorta induced
by systemic hypoxia: Biochemical and morphological studies.
Angiology 1969;20:1–12

65. Pietilä K, Jaakkola O: Effect of hypoxia on the synthesis of
glycosaminoglycans and collagen by rabbit aortic smooth mus-
cle cells in culture. Atherosclerosis 1984;50:183–190

66. Kolset SO, Kjellén L, Seljelid R, Lindahl U: Changes in
glycosaminoglycan biosynthesis during differentiation in vitro

67. Owens RT, Wagner WD: Chondroitin sulfate proteoglycan
and heparan sulfate proteoglycan secreted by macrophages in

68. Takasu Y, Hasuri F, Mori Y: Biosynthesis of glycosaminogly-
cans in peritoneal macrophages from the guinea pig. Biochim
Biophys Acta 1983;716:316–323

69. Piaas AHK, Ison AL, Ackland J: Synthesis of small proteogly-
cans substituted with keratan sulfate by rabbit articular chon-

KEY WORDS • artery • atherosclerosis • proteoglycans •
keratan sulfate • dermatan sulfate
Demonstration of a keratan sulfate-containing proteoglycan in atherosclerotic aorta.
R A Robbins, W D Wagner, T C Register and B Caterson

doi: 10.1161/01.ATV.12.1.83
Arteriosclerosis, Thrombosis, and Vascular Biology is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1992 American Heart Association, Inc. All rights reserved.
Print ISSN: 1079-5642. Online ISSN: 1524-4636

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://atvb.ahajournals.org/content/12/1/83

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Arteriosclerosis, Thrombosis, and Vascular Biology can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Arteriosclerosis, Thrombosis, and Vascular Biology is online at:
http://atvb.ahajournals.org//subscriptions/