Identification of a Novel Glycoprotein (AGp110) Involved in Interactions of Rat Liver Parenchymal Cells with Fibronectin

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Abstract. We have identified an integral membrane glycoprotein in rat liver that mediates adhesion of cultured hepatocytes on fibronectin substrata. The protein was isolated by affinity chromatography of detergent extracts on wheat germ lectin-Agarose followed by chromatography of the WGA binding fraction on fibronectin-Sepharose. The glycoprotein (AGp110), eluted at high salt concentrations from the fibronectin column, has a molecular mass of 110 kD and a pI of 4.2. Binding of immobilized AGp110 to soluble rat plasma fibronectin required Ca2+ ions but was not inhibited by RGD peptides. Fab' fragments of immunoglobulins raised in rabbits against AGp110 reversed the spreading of primary hepatocytes attached onto fibronectin-coated substrata, but had no effect on cells spread on type IV collagen or laminin substrata. The effect of the antiserum on cell spreading was reversible. AGp110 was detected by immunofluorescence around the periphery of the ventral surface of substratum attached hepatocytes, and scattered on the dorsal surface. Immunohistochemical evidence and Western blotting of fractionated liver plasma membranes indicated a bile canalicular (apical) localization of AGp110 in the liver parenchyma. Expression of AGp110 is tissue specific: it was found mainly in liver, kidney, pancreas, and small intestine but was not detected in stomach, skeletal muscle, heart, and large intestine. AGp110 could be labeled by lactoperoxidase-catalyzed surface iodination of intact liver cells and, after phase partitioning of liver plasma membranes with the detergent Triton X-114, it was preferentially distributed in the hydrophobic phase. Treatment with glycosidases indicated extensive sialic acid substitution in at least 10 O-linked carbohydrate chains and 1–2 N-linked glycans. Immunological comparisons suggest that AGp110, the integrin fibronectin receptor and dipeptidyl peptidase IV, an enzyme involved in fibronectin-mediated adhesion of hepatocytes on collagen, are distinct proteins.

Adhesive interactions between the hepatic parenchyma and the surrounding biomatrix are important in maintaining the morphological and functional integrity of the liver. The extracellular matrix can modulate the expression of liver-specific proteins (5, 25, 46, 55) and, in pathological conditions such as cirrhosis and fibrosis, impaired liver function may be related to significant alterations in the distribution and synthesis of extracellular matrix components (20, 47, 48).

The most abundant noncollagenous matrix constituent in adult rat liver is fibronectin, a major component of biomatrices of connective tissue or epithelial origin (1, 25, 49). In liver parenchyma, fibronectin is mostly present in the perisinusoidal space (39), but can also be detected on the lateral and bile canalicular cell surface domains (18, 25). Basement membrane proteins such as type IV collagen and laminin are sparsely distributed on the sinusoidal surface only (25, 39), but a typical basement membrane structure, as seen in other epithelia, has not been observed at the basal surface of liver parenchymal cells.

Hepatocytes in vitro attach and spread on extracellular matrix proteins including fibronectin (7, 30, 31) and a putative fibronectin receptor of rat hepatocytes has recently been isolated (32). This receptor belongs to the integrin family of proteins (29, 49) and binds to the Arg-Gly-Asp (RGD) sequence in the cell-binding domain of fibronectin, in common with some other integrins (49, 51). In this study we describe another protein from rat liver which mediates adhesion of hepatocytes on fibronectin matrices. This protein, AGp110, for apical glycoprotein of molecular mass 110 kD, is not related to the integrin-receptor family but its properties suggest strongly that it makes an important contribution to the adhesive interactions of liver parenchymal cells with fibronectin matrices.
Materials and Methods

Cells

Hepatocytes were isolated from young adult female Sprague-Dawley rats by liver perfusion with collagenase (6). Viable cells were further purified by Percoll isopycnic centrifugation (37), and cultured in arginine-free DME (36) supplemented with 0.5 mM ornithine, 0.1 mM insulin, 0.025 mM dextamethasone, 60 μg/ml penicillin, 100 μg/ml streptomycin, and 50 μg/ml gentamicin. Cell culture substrata were treated with either 25 mg/ml fibronectin, 40 μg/ml type IV collagen, or 40 μg/ml laminin in PBS for at least 1 h and washed with PBS; cells were then seeded and grown in serum-free medium.

Proteins and Enzymes

Fibronectin was purified from rat plasma on a gelatin-Sepharose column (17). Type IV collagen and laminin were isolated from the Engelbreth-Holm-Swarm (EHS) sarcoma implanted in lathyritic mice as described (36). Collagenase (type IV; Sigma Chemical Co., St. Louis, MO), ovalbumin, bovine albumin, lactoperoxidase, and glucose oxidase were purchased from Sigma Chemical Co. Wheat germ agglutinin was obtained from Pharmacia Fine Chemicals (Piscataway, NJ). GRGDS peptide was obtained from Calbiochem-Behring Corp. (La Jolla, CA). Glycosidase F (N-glycanase), endoglycosidase F (Endo F), and endo-α-N-acetylgalactosaminidase (O-glycanase) were purchased from Boehringer Mannheim, FRG, and O-glycanase was also obtained from Genzyme Corp. (Boston, MA): results using O-glycanase from these two sources were indistinguishable. Vibrio cholerae neuraminidase was from Calbiochem-Behring Corp.

Radioactive Labeling

For metabolic labeling, cell cultures in petri dishes were incubated in low-methionine medium for 1 h and then grown for 1-16 h in low-methionine medium containing 100 μCi/ml of [35S]methionine. In some experiments cell cultures were treated with 1 μM tunicamycin for 3 h followed by addition of [35S]methionine and labeling over a further 16 h.

Surface labeling was carried out according to the lactoperoxidase-catalyzed iodination procedure using carrier-free 125I (0.5 mCi/ml) as described (12, 24).

Electrophoretic Techniques

SDS-PAGE and two-dimensional electrophoresis were carried out as described (38, 44). Western blotting of proteins on nitrocellulose and detection using antibody probes was performed according to established procedures (10, 15) as described (54). For preparative electrophoresis, proteins were run on 7-12% SDS polyacrylamide gels under reducing conditions, further at 37°C with 50% methanol in 0.1 M Tris, pH 8.8. The destained fractions were dialysed versus Hepes-saline pH 7.1, 1 mM octyl glucoside, 25 mM NaCl was dialysed versus distilled H2O containing 1 mM octyl glucoside and then versus 20 mM piperoxide. HCl, pH 5, containing 25 mM octyl glucoside. The glycoprotein was then loaded onto the column and eluted with a linear NaCl concentration gradient (0-1 M NaCl) in 20 mM piperoxide, HCl pH 5, 25 mM octyl glucoside. Agp110 eluted at ~0.3 M NaCl.

Antibodies and Isolation of IgG Fragments

Antisera against rat plasma fibronectin and Agp110 were raised in rabbits by intradermal injection at several sites in Freund's adjuvant followed by weekly booster injections 5 wk after the primary injection. To obtain sufficient amounts of Agp110 to raise antibodies, we extracted crude liver plasma membranes with 0.3% deoxycholate and applied the extract to a WGA Sepharose column equilibrated in the same buffer. The binding fraction that eluted with 1 M N-acetyl-D-glucosamine was dialysed versus distilled H2O and lyophilized. The lyophilized sample was dissolved in electrophoresis sample buffer and run on preparatory SDS gels. The bands with M, ~110 kD were excised and electroeluted. This electroeluted antigen was used for injecting rabbits. Subsequent booster injections were with Agp110 isolated from bile canalicular membranes by WGA-agarose and fibronectin-Sepharose affinity chromatography. Rabbit antisera against the β-subunit of fibronectin receptor integrin and dipetidyl peptide IV (DPPIV) were kind gifts from Dr. S. Johansson (Biomedical Center, Uppsala, Sweden) and Dr. D. Doyle (State University of New York at Buffalo, NY), respectively. Anti-rabbit IgG/rodamine was obtained from Cappel Laboratories (Cochrannie, PA), anti-rabbit IgG/horseradish peroxidase and anti-rabbit IgG/alkaline phosphatase from Sigma Chemical Co.

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Affinity Chromatography

Rat plasma fibronectin and WGA were coupled to CNBr-activated Sepharose (5 mg/ml gel) as recommended (Pharmacia Fine Chemicals). Affinity chromatography on both WGA and fibronectin columns was performed at 4°C. Hepatocytes or purified canalicular membranes were extracted with 25 mM octyl glucoside in Hepes-saline (10 mM Hepes, pH 7.1, 150 mM NaCl) containing 1 mM PMSF, 1 mM NEM, 2 mM CaCl2, and 2 mM MgCl2. The extract was centrifuged for 30 min at 25,000 rpm in a rotor (model 42; Beckman Instruments, Fullerton, CA) and the clear supernatant was applied to a WGA-Sepharose column (5 × 2 cm) equilibrated with the same extraction buffer. Unbound material was removed by extensive washing with the same buffer and bound proteins were eluted with 1 M N-acetylglucosamine in buffer. Fractions (2 ml) were collected and peak fractions were dialysed versus Hepes-saline pH 7.1, 1 mM PMSF, 1 mM N-ethylmaleimide, 1 mM octyl glucoside. This fraction was made up to 25 mM octyl glucoside, 2 mM CaCl2, 2 mM MgCl2 and applied to a fibronectin-Sepharose column (5 × 2 cm) equilibrated in the same buffer as above. Elution of bound material was effected by 1 M NaCl in 10 mM Hepes, pH 7.1 containing 25 mM octyl glucoside or by 20 mM EDTA in the same buffer. 2-ml fractions were collected and peak fractions were pooled for further analysis.

Ion Exchange Chromatography

Agp110, isolated from bile canalicular membranes by WGA affinity chromatography followed by fibronectin affinity chromatography, was purified further by ion exchange chromatography on a Mono Q column using the Pharmacia FPLC system. Agp110 eluted from a fibronectin column with 1 M NaCl was dialysed versus distilled H2O containing 1 mM octyl glucoside and then versus 20 mM piperoxide. HCl, pH 5, containing 25 mM octyl glucoside. The glycoprotein was then loaded onto the column and eluted with a linear NaCl concentration gradient (0-1 M NaCl) in 20 mM piperoxide, HCl pH 5, 25 mM octyl glucoside. Agp110 eluted at ~0.3 M NaCl.

ELISA

The binding of Agp110 to fibronectin was investigated by an ELISA. In these experiments, we used Agp110 isolated from purified bile canalicular membranes by WGA-Agarose affinity chromatography, Fn-Sepharose affinity chromatography, and Mono Q FPLC ion exchange. Fibronectin was isolated from rat plasma. The purity of both proteins was confirmed by PAGE followed by silver staining.

Purified Agp110 was suspended in "sensitizing" buffer (4.5 ml of 0.2 M Na2CO3 and 8 ml of 0.2 M NaHCO3, made up to 50 ml with distilled water) containing 0.05% Tween 20 and dispensed in microtiter plate wells (~0.1 μg/100 μl Agp110 was used per well. The plates were then incubated overnight at 4°C. The wells were washed with PBS and unoccupied binding sites on polystyrene were blocked by incubation with 10% BSA in PBS pH 7.3 for 1 h at 37°C. A stock solution of fibronectin (630 μg/ml) was used at dilutions ranging from 1:5 to 1:5,000 and dispersed in 100-μl amounts in individual wells. The incubation buffer used was PBS pH 7.3 containing 1% BSA, 4 mM CaCl2, and 0.05% Tween 20. This buffer (incubation

1. Abbreviations used in this paper: DPPIV, dipetidyl peptidase IV; NEM, N-ethylmaleimide.

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buffer) was used for all subsequent reactions and washes. The plates were incubated with fibronectin for 1 h at 37°C and then extensively washed, and anti-fibronectin serum was added at a dilution of 1:200 and left for 1 h at 37°C. After extensive washing, the plates were incubated for 1 h at 37°C with anti-rabbit IgG conjugated to alkaline phosphatase (1:400). The wells were then exhaustively washed and alkaline phosphatse substrate (p-nitrophenyl phosphate from Sigma in sensitizing buffer containing 0.1% of 0.5 M MgCl2) was added (100 μl/well). Wells were developed with this chromogen for 2 h at 37°C. Absorbance at 400 nm was read in a Titertek Multiskan (Flow Laboratories, Mclean, VA).

Controls for these experiments consisted of wells with no absorbed AGp110 but otherwise processed as described above. These gave very low absorbance readings. The amount of AGp110 bound to fibronectin was determined by a standard curve. The reaction was stopped at 1 h, and the plates were developed with anti-rabbit IgG conjugated to alkaline phosphatase followed by chromogen substrate as described above. The ratio of absorbances (primary over secondary incubation) was ~10:1 with no significant variation among triplicate experiments. A third incubation did not give detectable absorbance. The amount of fibronectin linked to AGp110 was determined by referring to a standard curve. The reaction was stopped at 1 h, and the plates were developed with anti-rabbit IgG conjugated to alkaline phosphatase followed by chromogen substrate as described above. The ratio of absorbances (primary over secondary incubation) was ~10:1 with no significant variation among triplicate experiments. A third incubation did not give detectable absorbance. The amount of fibronectin linked to AGp110 was determined by referring to a standard curve.
Identification of AGp110

Rat hepatocytes seeded onto substrata derivatized with fibronectin were surface-labeled with \(^{125}\)I and extracted with octyl glucoside (see Materials and Methods). The detergent extract (Fig. 1a) was chromatographed on a wheat germ agglutinin-Agarose column and glycoproteins bound to the lectin were eluted with 1 M N-acetyl-D-glucosamine. This fraction (Fig. 1b) was applied to a fibronectin-Sepharose affinity column and proteins eluted with 1 M NaCl and 20 mM EDTA were analyzed by SDS electrophoresis (Figs. 1, c and d, respectively). The results indicated that a glycoprotein of molecular mass 110 kD was retained by the fibronectin column. Binding of AGp110 to fibronectin seemed to be specific under the experimental conditions described above since the protein was not retained in affinity columns of Sepharose derivatized with type IV collagen, laminin, albumin, or protein A or in columns of underivatized Sepharose. Elution of the fibronectin-Sepharose column by EDTA, i.e., by divalent ion chelation, indicated that binding of the glycoprotein to fibronectin required calcium and/or magnesium ions. Neither the high salt nor EDTA eluates contained proteins migrating in SDS gels with molecular weights similar to those observed (32) for the \(\alpha\) and \(\beta\) subunits of the liver integrin fibronectin receptor, 145 and 130 kD, respectively. We conclude that integrin does not bind to whole rat fibronectin under the experimental conditions used in our affinity chromatography and is presumably eluted with the flowthrough fraction (Fig. 1e). This fraction also appears to contain a major band of \(~\!110\) kD proteins. Rechromatography of the flowthrough fraction on the fibronectin column yielded additional amounts of the 110-kD component in the high salt and EDTA eluates and essentially complete depletion was reached only after three rounds of chromatography (results not shown). In all cases the flowthrough fraction contained other proteins of molecular mass \(~\!110\) kD, whose identity is discussed later.

Larger amounts of an AGp110 fraction were prepared from liver membranes and used to raise antibodies in rabbits. The antiserum reacted strongly with AGp110 purified from a fibronectin-Sepharose affinity column (Fig. 2a). In Western blots of two-dimensional gels of WGA-bound glycoproteins of liver membranes, reaction with anti-AGp110 revealed a single major spot at an indicated isoelectric point value of 4.2 (Fig. 2b).

In addition to chromatography, evidence for affinity of AGp110 for fibronectin was provided by ELISA experiments in which AGp110 was immobilized on microtiter wells and its association with rat plasma fibronectin was assessed using fibronectin-specific antibody probes. For these experiments AGp110 was purified to homogeneity from bile canalicular membrane preparations using WGA-Agarose and fibronectin-Sepharose affinity chromatography (Fig. 1f) followed by Mono Q FPLC (Fig. 1g). Fibronectin bound to immobilized AGp110 in a saturable manner (Fig. 3a). Binding was not RGD-directed since association was not significantly reduced by addition of the pentapeptide GRGDS (Fig. 3b). However,
Figure 3. Characteristics of AGp110 binding to rat plasma fibronectin. Points on graphs are mean values from triplicate experiments. Deviations from mean values are ~10%. Constant amounts of AGp110 (~0.1 μg) were immobilized on microtiter plate wells and incubated with fibronectin solutions of various concentrations. The wells were then incubated with rabbit anti-rat plasma fibronectin followed by anti-rabbit IgG conjugated with alkaline phosphatase. The OD_{400} values obtained after reaction with chromogen were compared with those of a standard curve for fibronectin, and the amount of fibronectin attached to immobilized AGp110 was quantitated. (a) Semi-log plot of added versus bound fibronectin. Saturable binding was observed. (b) Plot of fibronectin bound to AGp110 versus amount of soluble GRGDS peptide in incubation buffer. The result indicates minimal inhibition of binding. (c) Effect of calcium on fibronectin binding to AGp110. A significant reduction in the amount of fibronectin bound to AGp110 was observed in buffers lacking calcium.

Figure 4. Relative quantities of AGp110 in fractionated liver plasma membranes. 100 μg of membrane proteins from each membrane fraction were separated by SDS-PAGE, blotted onto nitrocellulose and treated with anti-AGp110 serum. (a) Lateral membranes; (b) canalicular membranes; (c) sinusoidal membranes.

Localization in Rat Liver Membranes
Western blotting of purified plasma membranes from the sinusoidal, lateral and canalicular cell surface domains of the liver parenchyma using anti-AGp110 serum indicated that the protein is located predominantly in the bile canalicular plasma membrane domain (Fig. 4). Secretion of AGp110 into the bile canaliculus does not seem to occur since the protein could not be detected in bile fluid by Western blottting (result not shown). Immunofluorescent staining of frozen liver sections (Fig. 5 a) affirmed antigen residency exclusively on the bile canalicular surface and provided no evidence for sinusoidal or lateral membrane localization, thus suggesting that the low level of expression of AGp110 found in Western blots of sinusoidal and lateral membranes (Fig. 5 b) is representative of the physiological surface expression of the protein.

AGp10 (≈0.1 μg) were immobilized on microtiter plate wells and incubated with fibronectin solutions of various concentrations. The wells were then incubated with rabbit anti-rat plasma fibronectin followed by anti-rabbit IgG conjugated with alkaline phosphatase. The OD_{400} values obtained after reaction with chromogen were compared with those of a standard curve for fibronectin, and the amount of fibronectin attached to immobilized AGp110 was quantitated. (a) Semi-log plot of added versus bound fibronectin. Saturable binding was observed. (b) Plot of fibronectin bound to AGp110 versus amount of soluble GRGDS peptide in incubation buffer. The result indicates minimal inhibition of binding. (c) Effect of calcium on fibronectin binding to AGp110. A significant reduction in the amount of fibronectin bound to AGp110 was observed in buffers lacking calcium.
Figure 5. Localization of AGp110 in frozen liver sections and in cultured hepatocytes by immunofluorescence. Immunofluorescent image of AGp110 localization using anti-AGp110 serum on frozen liver sections. The antigen is seen along the bile canaliculi. Bar, 20 µm. (b) Localization of AGp110 on live hepatocytes by immunofluorescence. Hepatocytes were cultured on fibronectin in serum-free medium at 37°C for 3 h before exposure to anti-AGp110 antibodies. The photograph depicts a double exposure at different focal planes. Focusing was on the substrate plane and close to the top cell surface. AGp110 is visualized along the periphery of the ventral surface close to the substratum and scattered over the dorsal cell surface. Bar, 10 µm.

4) is due to cross-contamination with membranes from the canalicular domain.

In vitro AGp110 was found on the substrate contact area along the periphery of the hepatocyte ventral surface, but was also scattered over the entire dorsal surface (Fig. 5b). The protein was neither incorporated into the fibronectin/fibrin matrix that hepatocytes synthesize in vitro (54) nor absorbed onto the fibronectin-coated culture substratum as shown by immunofluorescence experiments (results not shown).

AGp110 is exposed on the cell surface, since it was labeled by lactoperoxidase-catalyzed iodination of intact hepatocytes. To investigate the interaction of AGp110 with the membrane lipid bilayer, purified bile canalicular membranes were extracted with Triton X-114 or with buffers of high ionic strength, and the presence of the protein in each extract was probed with the antiserum in Western blots. AGp110 was found mainly in the detergent (hydrophobic) phase after Triton X-114 extraction and phase separation of canalicular membranes (Fig. 6, a and b) and could not be dissociated from the plasma membrane after treatment with 2 M NaCl (Fig. 6, c and d). On the basis of these experiments we conclude that AGp110 is an integral membrane protein of hepatocytes with an extracellular domain.

Role of AGp110 in the Adhesion of Rat Hepatocytes on Fibronectin

Since AGp110 was shown to be exposed on the hepatocyte cell surface and to interact with fibronectin, we investigated its possible role in hepatocyte adhesion to fibronectin by studying the effect of the AGp110 specific antiserum on hepatocytes cultured on fibronectin substrata.

Hepatocytes were allowed to spread on fibronectin substrata in serum-free medium in the presence of the protein synthesis inhibitor cycloheximide. The use of cycloheximide was deemed necessary in view of the fact that hepatocytes in vitro synthesize copious amounts of fibronectin and lesser amounts of other adhesive matrix proteins (such as type IV collagen and laminin) whose deposition on the substratum would have invalidated comparison of results from cells on different substrata (54–56). 3 h after inoculation monovalent Fab' fragments of anti-AGp110 IgG were added in the culture medium and caused rapid rounding of the cells (Fig. 7b) compared with control cultures (Fig. 7a). Control experiments using Fab' fragments of nonimmune rabbit IgG were totally negative. Ruffling activity at the peripheral lamella of spread hepatocytes could be noticed under the microscope just 10 min after adding the AGp110 specific antibodies. The adverse effect of anti-AGp110 Fab' fragments on hepatocyte spreading was independent of cell density and intercellular contacts: experiments in which hepatocytes were inoculated on fibronectin-coated substrata at different cell densities demonstrated that single cells or colonies of hepatocytes were equally prone to reversal of spreading after antibody treatment (results not shown). Fab' concentrations ranging from 500 to 50 µg/ml were tested and found to be effective in rounding up hepatocytes spread on fibronectin substrata. The cells remained viable throughout the antibody.
onto fibronectin could not be inhibited with Fab' concentrations up to 500 μg/ml (results not shown).

We also examined the effect of the antiserum on cells spread on type IV collagen or laminin substrata. As shown in Fig. 8, the anti-AGp110 Fab' fragments caused no noticeable reversal of cell spreading on either type IV collagen (Fig. 8 b) or laminin (Fig. 8 d) when compared with control cultures (Fig. 8, a and c, respectively).

**Glycosylation of AGp110**

Since AGp110 binds to WGA, it is clearly a glycoprotein. Further information on the extent and type of glycosylation was sought by making use of specific glycosidases. Hepatocytes spread on fibronectin were radioiodinated, extracted in 0.2% SDS (see Materials and Methods) and AGp110 was specifically immunoprecipitated. The immunoprecipitates were then digested with various glycosidases. Endo F, which cleaves high-mannose, hybrid, and some complex oligosaccharides attached through an N-linkage to asparagine, produced a small but reproducible molecular mass shift of ~2-3 kD (Fig. 9 b; compare with control, a). On the other hand, removal of sialic acid with neuraminidase reduced the molecular mass to 94 kD (Fig. 9 c), a reduction of 16 kD. Assuming complete removal of N-linked chains by Endo F, these results indicate an abundance of terminal sialic acid residues on carbohydrate chains O-linked to serine or threonine. However, since the protein may contain N-linked saccharides that are not cleaved by Endo F, we repeated the experiment using N-glycanase, which removes a broader range of complex asparagine-linked carbohydrate structures than endo F and O-glycanase, which releases O-glycans from serine or threonine. Since substitution with sialic acid at the core Gal(β1→3)GalNAc of O-glycans prevents release of this disaccharide, we first treated the immunoprecipitated AGp110 with neuraminidase: the asialoprotein migrated to 94 kD (Fig. 9 e) as noted in the previous experiment (Fig. 9 c). Subsequent hydrolysis with O-glycanase resulted in a molecular weight shift of ~5 kD (Fig. 9 f), confirming the presence of O-glycans. Digestion with N-glycanase increased the electrophoretic mobility of the protein (Fig. 9 g) by a magnitude similar to that obtained after Endo F hydrolysis (Fig. 9 b). These results indicate the presence of ~1-2 N-glycans and an abundance (at least 10 chains) of O-glycans. The number of carbohydrate chains cannot be determined accurately since removal of polysaccharides may alter the association of SDS with the protein, thus disproportionately affecting its mobility in SDS gels. Further proof on the extent of N-glycosylation was provided by examining the inhibitory effect of tunicamycin. Tunicamycin inhibits the first step of N-glycan assembly and hence blocks N-glycosylation completely. Metabolic labeling of hepatocytes with [35S]methionine in the presence of tunicamycin and subsequent immunoprecipitation of detergent-extracted proteins with anti-AGp110 yielded a band in SDS-gels at a molecular weight position of 107 kD (Fig. 9 k), consistent with the results obtained after Endo F (Fig. 9 b), and N-glycanase (Fig. 9 g) hydrolysis. Experiments in which cultures were pulsed for varying times (1-4 h) with isotope indicated the presence of a precursor of ~91 kD (Fig. 9, j-l) that is processed to yield the mature protein, as indicated after equilibrium labeling (Fig. 9 i).
Figure 8. Effect of AGp110 antibody on hepatocyte spreading on type IV collagen- or laminin-coated substrata. Bar, 50 μm. (a) Hepatocytes inoculated on type IV collagen and incubated for 3 h. (b) Cells incubated for 3 h on type IV collagen and then treated with medium containing 500 μg/ml Fab' fragments of anti-AGp110 antibodies for 1 h. (c) Hepatocytes spread on laminin after 3 h incubation. (d) Hepatocytes spread on laminin and then treated with anti-AGp110 Fab'.

Figure 9. Glycosylation and processing of AGp110. Autoradiograms of 7.5% SDS gels of immunoprecipitates of detergent-extracted surface-radioiodinated hepatocytes (a–g) and fluorograms of SDS gels of immunoprecipitates of detergent-extracted hepatocytes labeled metabolically with [35S]methionine (h–m). (a) Immunoprecipitation of detergent extracts of surface iodinated hepatocytes by specific AGp110 antibodies. (b) Endo F treatment of iodinated immunoprecipitated AGp110. (c) Neuraminidase treatment of iodinated AGp110. (d) AGp110 immunoprecipitated from surface-iodinated hepatocytes (same as a). (e) Neuraminidase-treated AGp110 (same as c). (f) Neuraminidase followed by O-glycanase treatment of AGp110. (g) N-glycanase treatment of AGp110. (h) AGp110 immunoprecipitated from extracts of cells that were metabolically labeled with [35S]methionine in the presence of tunicamycin. (i–l) Immunoprecipitation of AGp110 from hepatocytes labeled with [35S]methionine for 16 (i), 4 (j), 2 (k) and 1 h (l). A 91-kD precursor detected in short pulses is indicated.
Figure 11. Immunoprecipitation of AGp110 (a) and integrin (b) from surface radioiodinated cells extracted under nondissociating conditions. The gels (7.5%) were run in the absence of reducing agents. The arrows in b indicate the α and β subunits of fibronectin receptor integrin. Arrowheads indicate other proteins immunoprecipitated with the anti-β serum that could possibly be different integrin α subunits.

Figure 12. Relative amounts of AGp110 in various rat tissues. Equal amounts of protein (100 μg) from tissues extracted with octyl glucoside were subjected to SDS-PAGE. The separated proteins were transferred to nitrocellulose and probed with anti-AGp110 and peroxidase-conjugated anti-rabbit IgG.

**Comparison of AGp110 with Other Parenchymal Cell Surface Glycoproteins**

We compared AGp110 with the liver fibronectin receptor integrin (32) and DPPIV, an enzyme that is involved in fibronectin-mediated attachment of hepatocytes on collagen (21). Hepatocytes spread on fibronectin substrata were surface labeled by lactoperoxidase-catalyzed iodination and extracted under nondissociating conditions (see Materials and Methods). Aliquots of this extract were successively immunoprecipitated with anti-AGp110 serum (Fig. 10, a–d). The extracts thus immunodepleted of AGp110 were immunoprecipitated with antisera against integrin (Fig. 10 e) or DPPIV (Fig. 10 f). The results show that these proteins were present in the extract after AGp110 was removed, thereby indicating that AGp110 is a distinct glycoprotein.

In immunoprecipitations of AGp110 and integrin under nonreducing and nondissociating conditions (Fig. 11), we did not detect any change in the electrophoretic mobility of AGp110 in the absence of reducing agents (Fig. 11 a). The fact that a single band was observed in AGp110 immunoprecipitations under nondissociating conditions either in the presence (Fig. 10 a) or absence (Fig. 11 a) of reducing agents, suggests that the protein is a monomer. In contrast, the dimeric structure of the fibronectin receptor integrin was clearly revealed in nonreducing gels: the α and β subunits (Fig. 11 b, arrows) ran at indicated molecular masses of 155 and 118 kD respectively, in agreement with previous observations (32). The bands of higher molecular weight (Fig. 11 b, arrowheads) that were precipitated with the anti-β integrin antiserum could be different α subunits associated with the same β subunit of the fibronectin receptor.

**Tissue Distribution of AGp110**

The distribution of AGp110 in different tissues was determined by Western blotting of detergent extracts of tissues obtained from an adult rat. Equal amounts of protein from various tissues extracted with octyl glucoside (see Materials and Methods) were separated by SDS-PAGE, blotted onto nitrocellulose, and probed with anti-AGp110 (Fig. 12). The protein was found mainly in liver, pancreas, kidney, and small intestine. In the small intestine the protein migrated at a lower molecular mass (~90 kD), possibly due to proteolytic cleavage from digestive enzymes found in that organ. Lesser amounts of AGp110 were observed in lung, thymus, and spleen, but it was absent in stomach, large intestine, heart, and thigh muscle (Fig. 12). The results demonstrate that expression of AGp110 is tissue specific.

**Discussion**

We have identified and partially characterized a hepatic bile canalicular protein, AGp110, that interacts with fibronectin.
AGp110 is an integral membrane glycoprotein with an extracellular domain that is extensively glycosylated with sialylated O-glycans and one or two N-glycan chains. The functional significance of the binding to fibronectin was demonstrated in adhesion assays in which spreading of hepatocytes was arrested and reversed by antibodies to AGp110. In that respect therefore, the protein functions as a fibronectin receptor. The fibronectin receptor integrin of rat liver (32) and AGp110 seem to be distinct proteins: they migrate to different molecular weight positions in SDS gels, immunodepletion of AGp110 does not remove integrin from cell extracts and anti-AGp110 does not recognize the parenchymal integrin. Furthermore, the fact that our experiments indicate that the protein is a monomer without extensive intrachain disulfide bonding argues against it being a heterodimer or a β subunit from the integrin groups discovered so far (14, 29, 34).

Integrins are the major cell surface receptors for extracellular matrix components including fibronectin, but proteoglycans (50), gangliosides (11, 35), and other glycoproteins (2, 57) have also been shown to exhibit receptor-like activities in cell–fibronectin interactions. As regards the integrin family of macromolecules, fibronectin receptor integrins from liver parenchyma and endothelium have different α subunits but share a common β subunit (32, 33). T lymphocytes have two integrin receptors (58), which are dimers of the αβ1 and α4β1 type. In agreement with this, our experiments suggest that the β subunit (β1 type) of hepatocyte integrin (32) may associate with different α subunits to form multiple heterodimers. This plurality of cellular receptors corroborates findings on multiple ligand sites on the fibronectin molecule: the main cell adhesion fibronectin fragment contains the RG D cell recognition signal, while the heparin-binding domains activate adhesion by linkage to cell surface heparan sulfate (1, 29, 49, 51). The alternatively-spliced type III connecting segment (IIICS) that lies between the COOH-terminal heparin and fibrin domains has two adhesion-promoting sequences (26, 28): one of these (CS5) contains the peptide REDV (in human fibronectin—in the rat it mutates to RGDV [52]), which supports melanoma but not fibroblast cell attachment (26, 28), while the other (denoted CSI) induces neurite extension (27) and contains a peptide sequence recognized by the α5β1 integrin of peripheral blood and cultured T lymphocytes (58). The latter integrin has no affinity for RGD. In addition to these adhesion domains, evidence exists for yet another sequence operating in synergy with RGD (16). In this context, the discovery of a dual fibronectin receptor system in liver parenchyma, comprising AGp110 and as integrin(s), although novel, follows the concept of fibronectin receptor plurality as discussed above.

Our adhesion experiments show that initial attachment of hepatocytes on fibronectin are not blocked with anti-AGp110, whereas spreading of cells in 3-h-old cultures can be reversed. This indicates a minor (if any) role of AGp110 in initial contact to fibronectin, but a significant contribution in initiating or maintaining cell spreading. Since inhibition of integrin function with specific antisera also reverses spreading (30), active spreading may require co-operative action from both receptors, whereas integrin alone may suffice to effect initial attachment.

Among nonintegrin hepatic glycoproteins with molecular weight similar to AGp110, DPPIV is involved in fibronectin-mediated adhesion of hepatocytes on collagen (21). Apparently, DPPIV is found on the bile canalicular surface (22), although other data suggests a less polarized distribution (9). Our immunodepletion experiments (Fig. 10) and other serological comparisons using our anti-AGp110 serum and monoclonal antibodies against DPPIV indicate that DPPIV and AGp110 are distinct proteins. Cell-CAM 105, an intercellular adhesion molecule (41, 43) shows a low level of antigenic cross-reactivity with AGp110, but behaves differently under nonreducing conditions in SDS-PAGE and is N-glycosylated to a significantly higher degree that AGp110 (43), so identity is unlikely. A transformation-sensitive 110-kD glycoprotein has also been localized in bile canalicular plasma membranes, but has a slightly more acidic isoelectric point and displays a different tissue distribution (4). AGp110 may, however, be related to a monocyte fibronectin receptor described previously (23): this protein (Mr ~ 105 kD) is also a monomer with no indication of intrachain disulfide bonds.

The physiological role of a double-receptor system in the liver parenchyma is not clear. Multiple receptors for fibronectin could confer tissue specificity in adhesive interactions or mediate phenomena such as cell migration and selective adhesion in either normal programmed events, such as development, or in pathological conditions, such as the neoplastic state in which the spectrum of integrins is known to be altered (45). Fibronectin in rat liver shows an uneven, but essentially nonpolarized distribution with respect to the hepatocyte surface: the protein can be found on the canalicular and lateral surfaces (25) but is most prominent in the perisinusoidal space (25, 39). Recently, different fibronectin isoforms have been found on each hepatocellular surface domain (18), thus necessitating a sorting mechanism perhaps provided by different receptors. Such a putative role for AGp110 would not exclude a functional, perhaps transient, involvement in adhesive interactions in vivo under conditions where the strict polarization of the hepatocellular surface is perturbed such as during cell division in expansion of the liver parenchyma. Antigens found on the bile canalicular surface in adult liver have been shown to exhibit a different distribution in the embryonic liver (40), in hepatocarcinogenesis (53) and during liver regeneration after partial hepatectomy (42).

In conclusion, we have demonstrated the existence of a novel glycoprotein in liver parenchyma that is active in mediating spreading of cultured hepatocytes on fibronectin substrate. AGp110 and integrin fibronectin receptor are distinct proteins suggesting that a dual receptor system mediates cell–fibronectin interactions in the liver parenchyma.

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References

21. Hanski, C., T. Huhle, and W. Reutter. 1985. Involvement of plasma mem-


