RGD-independent Cell Adhesion to the Carboxy-terminal Heparin-binding Fragment of Fibronectin Involves Heparin-dependent and -independent Activities

James B. McCarthy, Amy P. N. Skubitz, Qi Zhao, Xiang-yan Yi, Daniel J. Mickelson, David J. Klein,* and Leo T. Furcht

University of Minnesota, Department of Laboratory Medicine and Pathology and *Department of Pediatrics, Minneapolis, Minnesota 55455

Abstract. Cell adhesion to extracellular matrix components such as fibronectin has a complex basis, involving multiple determinants on the molecule that react with discrete cell surface macromolecules. Our previous results have demonstrated that normal and transformed cells adhere and spread on a 33-kD heparin binding fragment that originates from the carboxy-terminal end of particular isoforms (A-chains) of human fibronectin. This fragment promotes melanoma adhesion and spreading in an arginyl-glycyl-aspartyl-serine (RGDS) independent manner, suggesting that cell adhesion to this region of fibronectin is independent of the typical RGD/integrin-mediated binding. Two synthetic peptides from this region of fibronectin were recently identified that bound [^{3}H]heparin in a solid-phase assay and promoted the adhesion and spreading of melanoma cells (McCarthy, J. B., M. K. Chelberg, D. J. Mickelson, and L. T. Furcht. 1988. *Biochemistry.* 27:1380–1388). The current studies further define the cell adhesion and heparin binding properties of one of these synthetic peptides. This peptide, termed peptide I, has the sequence YEKPGSP-PREVVPRPRPGV and represents residues 1906–1924 of human plasma fibronectin. In addition to promoting RGD-independent melanoma adhesion and spreading in a concentration-dependent manner, this peptide significantly inhibited cell adhesion to the 33-kD fragment or intact fibronectin. Polyclonal antibodies generated against peptide I also significantly inhibited cell adhesion to the peptide, to the 33-kD fragment, but had minimal effect on melanoma adhesion to fibronectin. Anti-peptide I antibodies also partially inhibited [^{3}H]heparin binding to fibronectin, suggesting that peptide I represents a major heparin binding domain on the intact molecule. The cell adhesion activity of another peptide from the 33-kD fragment, termed CS1 (Humphries, M. J., A. Komoriya, S. K. Akiyama, K. Olden, and K. M. Yamada. 1987. *J. Biol. Chem.*, 262:6886–6892) was contrasted with peptide I. Whereas both peptides promoted RGD-independent cell adhesion, peptide CS1 failed to bind heparin, and exogenous peptide CS1 failed to inhibit peptide I-mediated cell adhesion. The results demonstrate a role for distinct heparin-dependent and -independent cell adhesion determinants on the 33-kD fragment, neither of which are related to the RGD-dependent integrin interaction with fibronectin.

TUMOR cell adhesion to extracellular matrix components is a fundamental consideration of invasion and metastasis (Liotta et al., 1983; McCarthy et al., 1985). Over the last several years, it has been shown that the adhesion of normal and transformed cells to extracellular matrix proteins such as fibronectin has a complex molecular basis. The recognition of the arginyl-glycyl-aspartyl-serine (RGDS) sequence by cell surface integrin(s) is the best understood mechanism that cells use to adhere to fibronectin and other matrix and plasma proteins (Buck and Horwitz, 1987; Juliano, 1987; Hynes, 1987; Ruoslahti, 1988). Despite the importance of this interaction to cell adhesion, there is clear evidence indicating the involvement of other cell surface macromolecules and other biologically active domains on fibronectin.

We have previously demonstrated that a 33-kD heparin-binding fragment, which originates from the carboxy-terminal region of fibronectin A-chains, is active at promoting the RGD-independent adhesion and spreading of murine melanoma and fibrosarcoma cell lines (McCarthy et al., 1986, 1988*a*,*b*). This fragment can inhibit experimental metastasis when preincubated with tumor cells ex vivo before tail vein injection (McCarthy et al., 1988*b*). Other cell types, such as neurons from the developing chicken (Rogers et al., 1987), endothelial cells (Visser et al., 1989), and lymphocytes (Liao et al., 1989; Wayner et al., 1989) also adhere to this frag-

ment. An mAb raised against the 33-kD fragment was used to localize a melanoma adhesion-promoting activity on a region of this fragment, which excluded the type IIIcs connecting sequence (McCarthy et al., 1988*a*). This approach was complemented with the identification of two heparin-binding synthetic peptides that promoted melanoma cell adhesion (McCarthy et al., 1988*a*). The peptides, termed I and II, have different primary structures (YEKPGSPPREVVPRPRPGV and KNNQKSEPLIGRKKT, respectively) yet they share some common features, including a low (hydrophilic) hydropathy index and a positive net charge. Whereas both peptides bear a net positive charge, not all positively charged peptides produced from matrix proteins (e.g., laminin) will promote melanoma cell adhesion (Charonis et al., 1988), suggesting that charge alone is not the sole explanation for the activity of such peptides. That the fibronectin peptides bind both [^{3}H]heparin and promote cell adhesion suggests a role for cell surface heparin-like molecules (i.e., glycosaminoglycans or proteoglycans) in promoting melanoma cell adhesion to this region of fibronectin.

A synthetic peptide approach has also been used by others to identify an additional cell adhesion promoting domain within fibronectin A-chains (Humphries et al., 1987). Synthetic peptide CS1 has the primary structure DELPQLVTLPHPNLHGPEILDVPST and is present within the 33-kD heparin-binding fragment of human plasma fibronectin (McCarthy et al., 1988*a*). This peptide has been reported to promote cell adhesion and spreading and to promote neurite extension by dorsal root ganglion neurons (Humphries et al., 1987, 1988; Dufour et al., 1988). Peptide CS1 is located to the carboxy-terminal side of both RGDS and the carboxy-terminal heparin-binding domain of fibronectin. Further evidence suggests that yet another cell adhesion/spreading domain is located to the amino-terminal side of the RGDS sequence (Obara et al., 1988). While receptors for the heparin-binding cell adhesion promoting domains of fibronectin have yet to be identified, peptide CS1 has been shown to promote cell adhesion through an integrin-dependent mechanism. Anti-β1 integrin antibodies have been reported to perturb cell adhesion to peptide CS1 (Dufour et al., 1988; Humphries et al., 1988), and recently T lymphocyte adhesion to this region of fibronectin has been demonstrated to involve an $\alpha_4\beta_1$ integrin which is RGD-independent (Wayner et al., 1989).

These studies further examined the role for peptide I in melanoma cell adhesion and spreading. The results support the contention that peptide I, located within the carboxy-terminal heparin binding region of fibronectin, represents a major heparin-binding determinant that promotes cell adhesion in an RGDS-independent manner. Furthermore, the adhesion-promoting activity of this peptide and of peptide CS1 could be distinguished by several criteria, suggesting that the two peptides promote cell adhesion by distinct mechanisms.

Materials and Methods

Cell Culture

The cells used for these studies were the metastatic melanoma cell line K1735 M4, originally supplied as a generous gift from Dr. I. J. Fidler (Houston, TX). Cells were passaged in vitro in DMEM containing 10% calf serum by methods previously described (McCarthy et al., 1986, 1988*a*). The metastatic potential of this cell line has been previously confirmed by our laboratory (McCarthy et al., 1988*b*). Care was taken to limit the number of in vitro passages to 10 to minimize phenotypic drift.

Protein and Fragment Isolation

Human plasma fibronectin was purified as a byproduct of Factor VIII production by sequential ion-exchange and gelatin affinity chromatography as described (McCarthy et al., 1986, 1988*a*). The 33-kD heparin binding fragment, which originates from A-chains of fibronectin, was purified from tryptic/catheptic digests of intact fibronectin using sequential gelatin, heparin, and antibody affinity columns as described previously (McCarthy et al., 1988*a*). Laminin and type IV collagen were purified from the murine Englebreth-Holm-Swarm tumor as described previously (Herbst et al., 1988). The purity of intact proteins and the 33-kD fragment of fibronectin was verified by SDS-PAGE and Coomassie brilliant blue staining.

Peptide Synthesis and Characterization

Peptides from fibronectin were synthesized at the Microchemical Facility of the University of Minnesota by Dr. Robert Wohlheuter using a peptide synthesizer (System 990; Beckman Instruments Co., Fullerton, CA). The procedures used were based on the Merrifield solid-phase system as described previously (Stewart and Young, 1984). Lyophilized crude peptides were purified by preparative reverse-phase HPLC on a C-18 column, using an elution gradient of 0–60% acetonitrile with 0.1% trifluoracetic acid in water. The purity and composition of the peptides was verified by HPLC analysis of hydrolysates prepared by treating the peptides under nitrogen in 6 N HCl overnight at 110°C. The peptides included heparin binding peptides I and II (McCarthy et al., 1988*a*), which have the sequences YEKPGSPPREVVPRPRPGV and KNNQKSEPLIGRKKT, respectively. Peptide CS1, which has the sequence DELPQLVTLPHPNLHGPEILDVPST (Humphries et al., 1987) was also synthesized. The sequences shown use the single-letter amino acid code (K = lysine, R = arginine, H = histidine, E = glutamic acid, D = aspartic acid, Q = glutamine, N = asparagine, P = proline, G = glycine, S = serine, T = threonine, V = valine, I = isoleucine, L = leucine, Y = tyrosine).

Coupling of Synthetic Peptides to IgG

Peptides I and CS1 were coupled to normal rabbit IgG as suggested by Humphries et al. (1987). However, we used carbodiimide as a coupling reagent, based on a procedure described previously (Bauminger and Wilchek, 1980). Briefly, equal amounts (by weight) of peptide and IgG were solubilized in water and mixed with a 10-fold excess (by weight) of 1-ethyl-3 (3-dimethylaminopropyl)-carbodiimide hydrochloride (Sigma Chemical Co., St. Louis, MO) dissolved in water. The sample was then mixed overnight at 4°C on a circular rotator. The coupled peptide was then dialyzed extensively in PBS to remove the excess carbodiimide and uncoupled peptide (10,000-D exclusion; Spectrum Medical Industries, Los Angeles, CA).

Cell Adhesion Assays

The cell adhesion assay was essentially the same as described previously (Skubitz et al., 1987). Briefly, purified fibronectin, 33-kD heparin-binding fragment of fibronectin, or the various synthetic peptides were diluted to various concentrations in PBS, and 50-μl aliquots were dispensed in triplicate to microtiter wells (Immulon 1; Dynatech Laboratories, Chantilly, VA). The wells were dried overnight in a 29°C oven, and nonspecific sites on the plastic were then blocked for 3 h by treating the wells with 200 μl of PBS containing 2 mg/ml fatty acid–free BSA (Miles Laboratories, Elkhart, IN). Alternatively, purified fibronectin, normal rabbit IgG, or the peptides that were coupled to normal rabbit IgG were diluted in PBS and 100-μl aliquots were dispensed in triplicate into microtiter wells. The wells were incubated at room temperature for 60 min as described (Yamada and Kennedy, 1984; Humphries et al., 1987), nonadsorbed proteins were removed, and the wells were incubated with 2 mg/ml BSA in PBS for 3 h.

Subconfluent K1735 M4 melanoma cells, which had been radiolabeled overnight with tritiated thymidine, were released from culture flasks by trypsin/EDTA, washed, and adjusted to a concentration of 5×10^4 cells per ml of DME containing 0.15 mM Hepes (pH 7.2) and 2 mg/ml BSA. The cells were dispensed in a volume of 100 μl to the microtiter wells. Depending on the experiment, the incubation time for the assay ranged from 30 min to 2 h. The assays were terminated by aspirating loosely bound and unbound cells from the wells, washing the wells three times, and solubilizing the bound cells in 0.5 N NaOH containing 1% SDS. Bound radioactivity, deter-

mined in a liquid scintillation counter (model 3801; Beckman Instruments Co.), was used to calculate the percentage of cells adherent in each sample. In parallel experiments, adherent cells were fixed with 2% glutaraldehyde in PBS and photographed on a Nikon Diaphot inverted-phase microscope.

Cell adhesion was inhibited both by synthetic peptides and polyclonal antibodies raised against the synthetic peptides. To test for inhibition of cell adhesion by synthetic peptides, cells were first preincubated in various concentrations of synthetic peptides for 30 min before the cell adhesion assay. The exogenous peptides were included in the adhesion assay for the duration of the experiment. When antibodies were tested for inhibition of cell adhesion, various concentrations of purified immunoglobulins generated against peptide I or normal rabbit immunoglobulin were diluted in the cell adhesion medium and preincubated on the plates for 30 min before the addition of cells. As was the case for the peptide inhibition experiments, the antibodies remained in the cell adhesion assay for the duration of the experiment. After the 30-min preincubation, the cells were incubated in the protein-coated wells for 30 min. Nonadherent cells were then aspirated off, the wells were washed, and bound cells were quantitated as described above.

Purification of Commercial [^{3}H]Heparin

Before use in the [^{3}H]heparin solid-phase binding assays, commercial [^{3}H]heparin (0.03 mCi/mg sp act; ICN Immunobiologicals, Lisle, IL) was first purified to create a sample that was homogeneous by size and charge. The [^{3}H]heparin was firsi applied to a Sephadex G-50 column (0.5 × 25 cm) equilibrated in 0.1 M ammonium formate. The radioactivity in the void volume (V_o) of this column was concentrated by lyophilization and resuspended in the starting buffer (DEAE buffer) for the (DEAE) ion exchange column: 0.05 M Tris-HCl, pH 7.0, containing 6 M urea, 0.1 M NaCl, and 0.2% CHAPS. [^{3}H]Heparin was purified by HPLC (model 110 A; Beckman Instruments Co.) using a 7.5 × 75 mm TSK DEAE 5PW anion-exchange column (Bio-Rad Laboratories, Richmond, CA). The sample was applied at a flow rate of 1 ml/min, and the column was washed with 20 column volumes of DEAE-buffer. [^{3}H]Heparin was eluted with a linear salt gradient from 0.1 M to 0.8 M NaCl over 45 min (a rate of 0.015 M/min). The radioactive peak from this column was dialyzed against water, concentrated by lyophilization, and resuspended in 0.5 M sodium acetate buffer containing 0.2% CHAPS. The hydrodynamic size of [^{3}H]heparin was estimated by gel filtration on 0.9 × 110 cm Sepharose CL-6B columns. The columns were equilibrated and eluted with 0.5 M sodium acetate containing 0.2% CHAPS, pH 7.0, at a flow rate of 3 to 4 ml/h (Klein et al., 1986). Fractions of 1.0–1.2 ml were collected with a 95% recovery of radioactivity. Rat chondrosarcoma chondroitin sulfate proteoglycan (Oegema et al., 1975) associated with 4% hyaluronic acid, and glucuronolactone, were used to mark the column void (V_o) and total (V_t) volumes, respectively. [^{3}H]Heparin chain size was estimated based on the previous data of Wasteson (1971). The concentration of the purified [^{3}H]heparin was determined by uronic acid analysis as described previously (Bitter and Muir, 1964).

Solid-Phase [^{3}H]Heparin Binding Assay

The ability of the various ligands to bind purified [^{3}H]heparin was assessed using a solid-phase binding assay that used either Immulon 1 plates (Skubitz et al., 1988) or Immulon C plates (McCarthy et al., 1988*a*) as a support. In either case, the substrata were prepared by drying the various ligands onto the surface of the wells as for the cell adhesion assays. The plates were then blocked with PBS/BSA, and purified [^{3}H]heparin was added to the wells in PBS/BSA. The plates were incubated for 2 h at 37°C, at which time they were washed 5 times with PBS to remove the unbound [^{3}H]heparin. The bound [^{3}H]heparin was solubilized with 0.5 N NaOH containing 1% SDS, and the radioactivity in each sample was quantitated as described above.

In certain experiments, unlabeled heparin (molecular mass 15 kD, Sigma Chemical Co.), dextran sulfate (molecular mass 8 kD, Sigma Chemical Co.) or chondroitin-4 sulfate glycosaminoglycans from the rat Swarm chondrosarcoma (Oegema et al., 1975; molecular mass 20 kD, generously supplied by Dr. T. R. Oegema) were used in competition assays for [^{3}H]heparin binding to the various ligands. For these experiments, various concentrations of competitor were mixed in PBS/BSA with subsaturating levels of [^{3}H]heparin before addition to the assay, and the assay performed as described above.

Purified immunoglobulin generated against peptide I was also tested for the ability to inhibit [^{3}H]heparin binding to intact fibronectin. For these assays, various concentrations of purified anti-peptide I immunoglobulin or normal rabbit immunoglobulin were diluted in PBS/BSA and incubated on fibronectin coated plates at 37°C for 30 min before the assay. A subsaturating level of [^{3}H]heparin was then added to the wells, incubated, and quantitated as described above.

Generation and Purification of Polyclonal Antibodies against Peptide I

Polyclonal antibodies were generated against heparin binding peptide I coupled to keyhole limpet hemocyanin (KLH[1], Sigma Chemical Co.) using carbodiimide as a coupling reagent, as described above for coupling to normal rabbit IgG. However, after the coupling reaction, the coupled peptide was dialyzed in Spectrapore 6 tubing (Spectrum Medical Industries) with an 1,000-D exclusion so that only the excess carbodiimide was removed and any uncoupled peptide would remain in the tubing. This mixture was then concentrated in Aquacide II (Calbiochem-Behring Corp., La Jolla, CA) to a final concentration of 10 mg/ml, and aliquots were stored at −70°C. The coupling of the peptide to KLH was verified by the use of radioiodinated peptide in a parallel reaction mixture.

The coupled mixture was then used to immunize New Zealand White Rabbits. Immunization was performed by mixing an equal volume of peptide/KLH conjugate with CFA and injecting this mixture into multiple sites on the shaved backs of the rabbits (~2 mg of conjugate/rabbit). Subsequent biweekly boosts in incomplete Freund's adjuvant were injected i. m. into the hind legs of rabbits. Sera were collected 7–10 d after the sixth immunization, and tested by ELISA for reactivity against uncoupled peptide I and various other ligands.

IgG was purified from pooled immune sera by precipitation with a final concentration of 45% ammonium sulfate overnight at 4°C. The precipitate was pelleted by centrifugation, resolubilized, and dialyzed against 0.035 M NaCl in 0.025 M Tris, pH 8.2. The IgG was purified over a DEAE anion exchange column as described previously (Skubitz et al., 1988). Purity of the IgG was determined by SDS-PAGE and Coomassie brilliant blue staining of the gel. Retained immunoreactivity of the purified IgG was verified by ELISA.

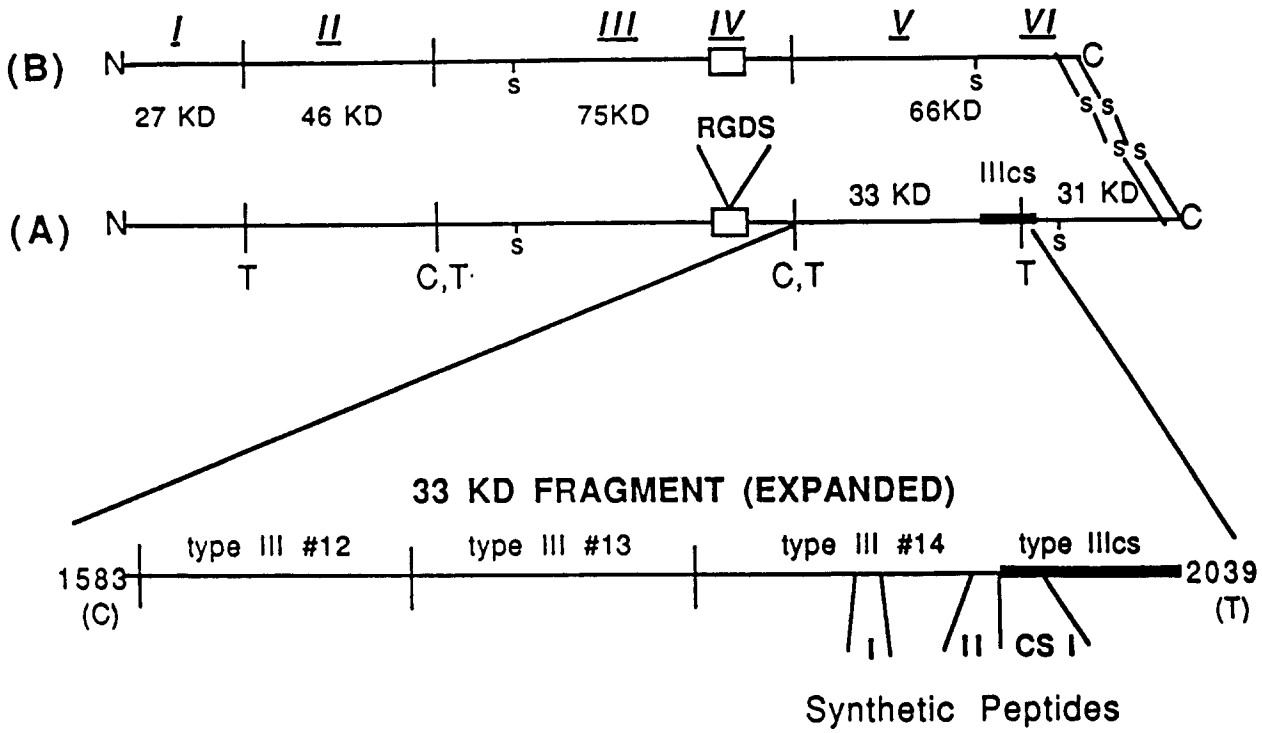
ELISA plates (either Immulon I or C) were prepared as for the cell adhesion assays by drying 1 μg/well of the various ligands onto the plates, except Vollers buffer was used to dilute the ligands (Smith and Furcht, 1982). The plates were then blocked by incubating the wells for 2 h at room temperature with PBS containing 2 mg/ml of ovalbumin (PBS/OA). Various concentrations of purified IgG were diluted in PBS containing 0.05% Tween 20 and 0.36 M NaCl (PBS/Tween) and incubated on the plates for 1 h at room temperature on a rotating platform. The plates were washed three times with PBS/Tween and incubated an additional hour with a 1:500 dilution of peroxidase-conjugated goat anti-rabbit immunoglobulin (Cappel Laboratories, Malvern, PA). The plates were washed extensively with PBS/Tween and developed with the subsequent addition of 0.4 mg/ml of orthophenylene diamine containing 0.012% H_2O_2 in 0.1 M sodium phosphate and 24 mM citric acid. The reaction was terminated by the addition of 2.5 M H_2SO_4 and the intensity at 490 nm determined using an automatic microplate reader (model EL311; Bio-Tek Instruments, Burlington, VT).

Results

Peptides I and CS1 Promote RGD-independent Melanoma Cell Adhesion by Distinct Mechanisms

Synthetic peptides I and CS1 are clearly distinct in terms of primary structure, hydropathy profiles, and charge (Fig. 1). Peptide I, which is in type III repeat #14 of human plasma fibronectin (Fig. 1, Kornbliht et al., 1985), represents residues 1906–1924, and would be predicted to occur in all isoforms of fibronectin identified to date (Hynes, 1985). Peptide CS1 represents residues 1961–1985 and occurs only on a subset of human plasma fibronectin molecules (Kornbliht et al., 1985). The hydropathy values, which were calculated by the method of Kyte and Doolittle (1982), were determined by stepwise averaging across a window of 6 residues. According to this method, the more hydrophobic regions of the peptides correspond to the more positive numerical values. Overall,

1. *Abbreviations used in this paper*: CS, chondroitin-4 sulfate; KLH, keyhole limpet hemocyanin; OA, ovalbumin.



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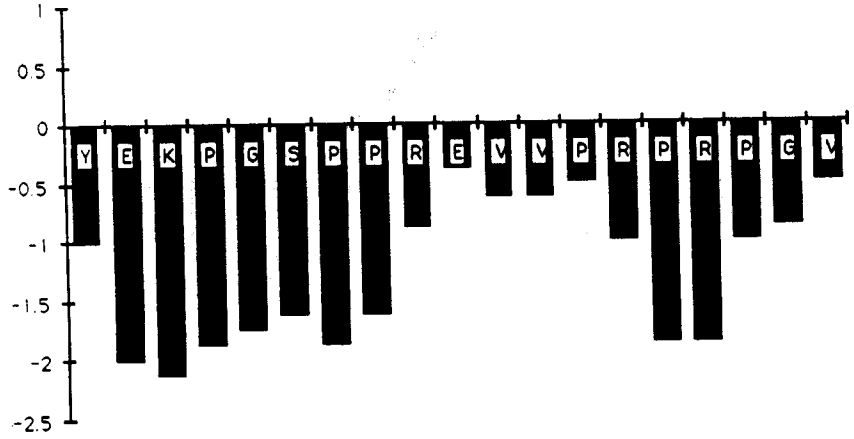

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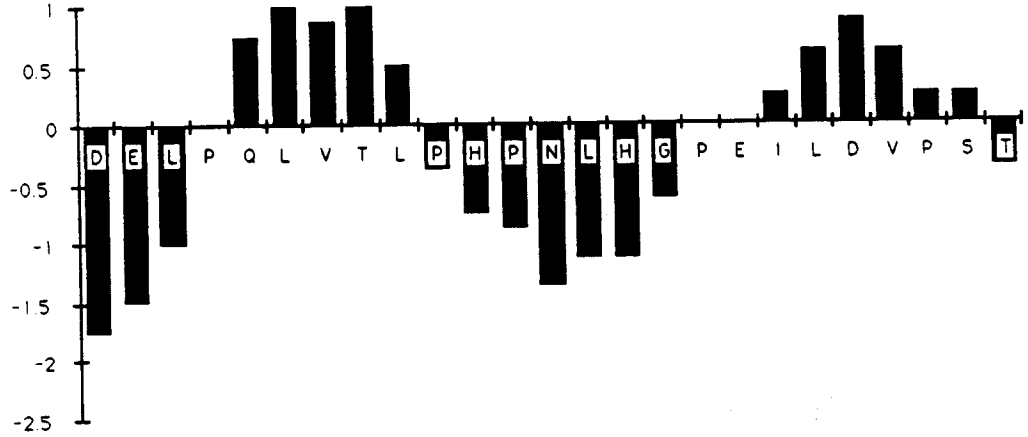

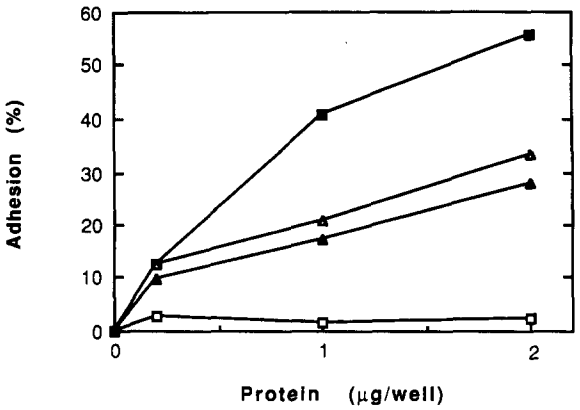

Figure 2. Adhesion of melanoma cells to increasing concentrations of synthetic peptides. Cells were radiolabeled and incubated for 2 h at 37°C in microtiter wells coated with various concentrations of fibronectin (■), peptide I (△), peptide CS1 (▲), or BSA (□) as described in Materials and Methods. Each value represents the mean of three separate determinations, and the SEM was <5% in each case. Three separate experiments gave similar results.

peptide CS1 is significantly more hydrophobic than peptide I (total net hydropathy indices of −9.9 and −24.3, respectively), with two hydrophobic regions distributed on either side of a slightly hydrophilic region. In contrast, peptide I is amphipathic, containing two extremely hydrophilic regions which surround a relatively hydrophobic central portion of the peptide. Peptide CS1 also carries a net negative charge (−4) at neutral pH, in contrast to peptide I which is cationic in nature (+2 net charge).

Uncoupled peptides I and CS1, adsorbed directly to plates, promoted melanoma cell adhesion in a concentration-dependent manner (Fig. 2). The maximum level of adhesion (~35% of input cells) observed on peptide I (2 μg/well) was ~60% of that observed on intact fibronectin, and was virtually equivalent to cell adhesion levels on peptide CS1. Similar results were obtained when substrata were coated with peptides which had been coupled to IgG (data not shown).

Melanoma cell spreading also occurred on substrata coated with peptide I, regardless of whether or not the peptide had been coupled to IgG (compare Fig. 3, *a* and *b*); however, the rate of spreading on peptide I was somewhat slower than that observed on intact fibronectin (not shown). By contrast, the ability of cells to spread on substrata coated with peptide CS1 was directly dependent on whether or not the peptide had been coupled to IgG before coating. Substrata coated with peptide CS1 coupled to IgG (Fig. 3 *c*) spread to the same extent as cells adherent on peptide I-coated substrata or substrata coated with intact fibronectin (Fig. 3 *e*). However, when substrata were coated with peptide CS1 that had not been coupled, very few cells exhibited a spread morphology (Fig. 3 *d*), despite the fact that such substrata could support the same level of cell adhesion as peptide I-coated substrata (Fig. 2). Virtually no adhesion and spreading of cells occurred on substrata coated with sham coupled IgG (Fig. 3 *f*) or BSA (not shown).

Our previous results (McCarthy et al., 1986, 1988*a*) as well as the results of others (Wayner et al., 1989) demonstrated that cell adhesion to the 33-kD fragment of fibronectin is independent of the RGDS cell adhesion sequence. Therefore, the effect of exogenous GRGDSP on melanoma cell adhesion to peptides I and CS1 was examined (Fig. 4). In agreement with our previous results, exogenous GRGDSP was virtually ineffective at inhibiting cell adhesion to the 33-kD fragment of fibronectin. However, GRGDSP was effective at inhibiting melanoma cell adhesion to intact fibronectin, with a maximum level of 50% inhibition observed in the presence of 600 μg/ml GRGDSP. Importantly, cell adhesion to peptides I and CS1 was unaffected by the addition of GRGDSP, even at concentrations which maximally inhibited cell adhesion to intact fibronectin (Fig. 4). These results indicate that the adhesion determinants within both synthetic peptides constitute major RGDS-independent cell adhesion sites within the 33-kD fragment of fibronectin. As controls in this study, GRGDSP was observed to have no effect on cell adhesion to laminin- or type IV collagen–coated substrata (data not shown).

Exogenous peptide I inhibited cell adhesion on substrata coated with fibronectin, peptide I, or the 33-kD fragment in a concentration-dependent manner (Fig. 5 *A*). The inhibition profiles on all three substrata were remarkably similar. However, the maximum level of inhibition on peptide I (~70%) was greater than the maximum inhibition observed on either the 33-kD fragment or intact fibronectin (~50%). CS1-mediated cell adhesion, in contrast, was totally resistant to competition with peptide I, even at a concentration of 600 μg/ml of exogenous peptide I. Exogenous peptide I also had no effect on melanoma cell adhesion to laminin or type IV collagen (data not shown).

Exogenous peptide CS1 inhibited cell adhesion to substrata coated with intact fibronectin, the 33-kD fragment, and peptide CS1 itself (Fig. 5 *B*). The inhibition profiles on substrata coated with intact fibronectin and the 33-kD fragment were similar, with maximum levels of inhibition at ~40%. Adhesion to peptide CS1 was most sensitive to the

Figure 1. Location of synthetic peptides within intact fibronectin and hydropathy profiles of peptides I and CS1. Shown is a schematic diagram depicting the location of the 33-kD carboxy-terminal heparin binding fragment within fibronectin and the two synthetic heparin binding peptides (peptides I and II) as well as peptide CS1. In contrast to peptides I and II, which are present within a type III homology common to all isoforms of fibronectin, peptide CS1 is restricted to isoforms of human plasma fibronectin that contain the type IIIcs region (A-chains). The amino terminal end and the carboxy-terminal limit of the 33-kD fragment is based on previous sequence data (McCarthy, 1988*a*). Selected biological domains, indicated by italicized, underlined roman numerals at the top of the figure, are based on the nomenclature of Furcht (1981). (*I*) Weak heparin binding; (*II*) collagen binding (noncovalent); (*III*) free sulfhydryl; (*IV*) RGD-mediated cell adhesion; (*V*) carboxy-terminal strong heparin binding and cell adhesion; (*VI*) free sulfhydryl. Approximate locations of tryptic (*T*) and cathepsin D (*C*) sites on intact fibronectin are shown. The sequences and hydropathy profiles for peptides I and CS1 are shown in the lower portion of the figure. The hydropathy profiles are calculated across a six-residue window and are based on the values of Kyte and Doolittle (1982). According to this method, the more positive values reflect increasingly hydrophobic character.

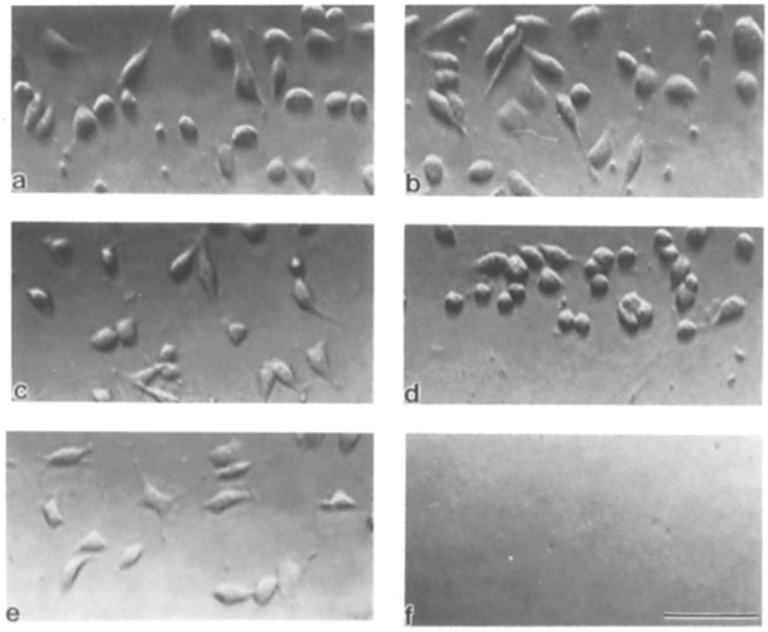

Figure 3. Spreading of melanoma cells on surfaces coated with synthetic peptides. Peptides I (*a*) and CS 1 (*c*) were coupled to IgG as described in Materials and Methods and diluted to a final concentration of 500 μg/ml IgG. Wells were then coated with 100 μl of peptide:IgG conjugate or IgG alone (*f*). Alternatively, wells were coated with 1 μg of uncoupled peptide I (*b*), CS 1 (*d*), or intact fibronectin (*e*). Cells were then incubated for 2 h at 37°C in these microtiter wells and photographed as described in Materials and Methods. Bar in *f*, 45 μm. Two separate experiments gave similar results.

effects of soluble peptide CS1 (70% maximum). Importantly, peptide I-mediated cell adhesion was totally resistant to the effects of soluble peptide CS1 at all concentrations. Cell viability, as assessed by trypan blue dye exclusion after a 1-h incubation in peptides, was >90% in all of these assays.

Polyclonal IgG against Peptide I Specifically Inhibits Peptide I-mediated Melanoma Cell Adhesion

Polyclonal antibodies were generated in rabbits against peptide I coupled to KLH. Immune sera were collected and the purified IgG screened by ELISA for immunoreactivity against various ligands. Anti-peptide I IgG reacted very well with intact fibronectin, the 33-kD fragment, and peptide I (Fig. 6); however, as would be expected, the extent of reactivity was much greater towards peptide I than towards the 33-kD fragment or intact fibronectin. This IgG was quite specific because it did not react by ELISA against substrata coated with ovalbumin, peptide CS1, or fibronectin peptide II (see Fig. 1), which also binds [^{3}H]heparin and promotes melanoma cell adhesion (McCarthy et al., 1988*a*). In addition, the anti-peptide I IgG did not react with laminin, type IV collagen, or BSA (not shown).

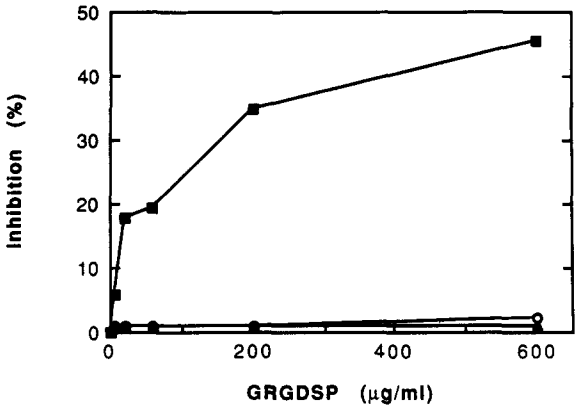

Figure 4. Peptide I- and peptide CS1-mediated cell adhesion is RGDS-independent. Cells were preincubated in the indicated concentrations of the hexapeptide GRGDSP for 30 min at 37°C and then added to wells coated with 1 μg fibronectin (■), or 2 μg of 33 kD fragment (○), peptide I (△), or peptide CS1 (▲). The assay was terminated 30 min later as described in Materials and Methods and the percentage of adherent cells was determined. The percent inhibition of cell adhesion was quantitated as: (1 minus [the number of cells bound in the presence of the inhibitor divided by the number of cells bound in the absence of the inhibitor]) multiplied by 100. Each value represents the mean of three separate determinations, and the SEM was <5% in each case. Three separate experiments gave similar results.

The effect of anti-peptide I IgG on cell adhesion to various ligands was next determined (Fig. 7). Increasing concentrations of IgG were extremely effective at inhibiting melanoma cell adhesion to the 33-kD fragment, with a highly significant (70%) inhibition observed in the presence of 500 μg/ml of anti-peptide I IgG. This IgG was even more effective at inhibiting cell adhesion to substrata coated with peptide I, with a virtually complete (95%) inhibition observed at the highest concentration of IgG. In contrast, anti-peptide I IgG was minimally effective (20–25%) at inhibiting adhesion to intact fibronectin, which would be expected since cells should be able to adhere to RGD-related and other adhesion sequences within fibronectin not recognized by the antibodies. Anti-peptide I IgG had no effect on cell adhesion to laminin, peptide CS1, or peptide II (not shown). Normal rabbit immunoglobulin had no effect on melanoma cell adhesion to any of the substrata tested (data not shown).

Peptide I (But Not CS1) Represents a Major Heparin-binding Determinant on Intact Fibronectin

The ability of peptides I and CS1 to bind [^{3}H]heparin were compared using a solid-phase binding assay in which the peptides were bound to the substrata. Before use in these assays, commercial [^{3}H]heparin was first purified to obtain a fraction that was relatively homogenous in size and charge

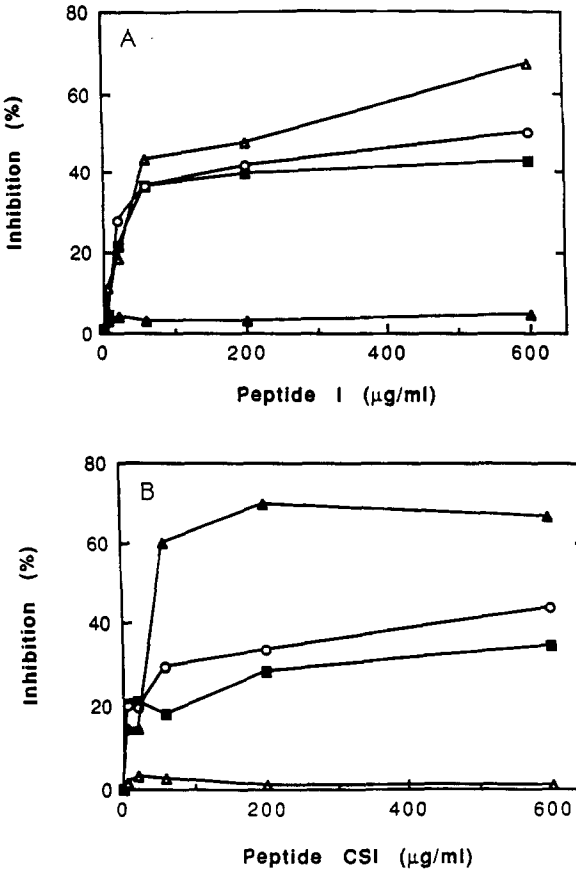

Figure 5. Effects of exogenous peptide I and peptide CS1 on melanoma cell adhesion. Radiolabeled cells were preincubated for 30 min in increasing concentration of (*A*) peptide I or (*B*) peptide CS1, then added to wells coated with 1 μg of fibronectin (■), 2 μg 33-kD fragment (○), peptide I (△), or peptide CS1 (▲). After a 30-min incubation, the nonadherent cells were aspirated off and the wells were washed three times. Adherent cells were quantitated in a scintillation counter. The percent inhibition of cell adhesion was quantitated as: (1 minus [the number of cells bound in the presence of the inhibitor divided by the number of cells bound in the absence of the inhibitor]) multiplied by 100. Each value represents the mean of three separate determinations, and the SEM was <10% in each case.

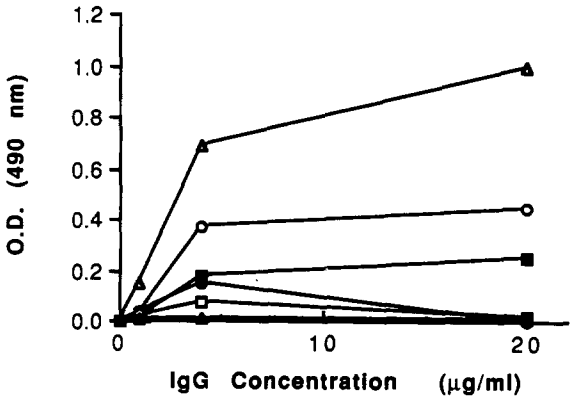

Figure 6. Reactivity of purified IgG raised against peptide I-KLH. Plates were coated with 1 μg of fibronectin (■), the 33-kD fragment (○), peptides I (△), II (●), CS1 (▲), or OA (□). Purified IgG from rabbits immunized with peptide I coupled to KLH was then added to the wells at the indicated concentrations. The ELISA was then performed as described in Materials and Methods and absorbance readings at 490 nm were taken. The values shown represent the average of triplicate wells with background readings using normal rabbit IgG subtracted. Four experiments gave similar results.

characteristics. The V_0 fractions of a Sephadex G-50 chromatographic separation of commercial [^{3}H]heparin (Fig. 8 *A*) were pooled, applied to an HPLC-DEAE anion exchange column and eluted as a single, sharp peak from this column at a salt concentration of 0.56 M NaCl (Fig. 8 *B*). This radioactive peak was pooled, concentrated, and applied to an analytical Sepharose CL-6B column from which it eluted at K_{av} 0.68 (Fig. 8 *C*). The procedure yielded [^{3}H]heparin with an estimated molecular weight of ~8 kD (according to the data of Wasteson, 1977) and a specific activity of 0.08 mCi/mg uronic acid.

Purified [^{3}H]heparin bound in a concentration dependent manner to substrata coated with fibronectin, the 33-kD fragment, or peptide I (Fig. 9). The binding of [^{3}H]heparin to each of these ligands was specific as a 100-fold excess of unlabeled heparin completely inhibited binding. In contrast, substrata coated with 5 μg/well of peptide CS1 were totally ineffective at binding [^{3}H]heparin, despite the fact that such substrata could promote melanoma cell adhesion. Increasing the coating concentration of peptide CS1 to levels as high as 10 μg/well failed to promote the binding of [^{3}H]heparin (data not shown).

The effect of various salt concentrations on the [^{3}H]heparin binding of fibronectin, the 33-kD fragment, and peptide I was compared (Table I). At physiological salt concentrations (0.15 M), each of the three ligands bound [^{3}H]heparin to es-

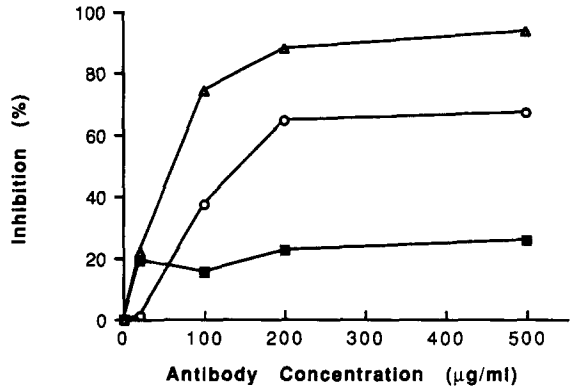

Figure 7. Effect of anti-peptide I antibodies on melanoma cell adhesion to intact fibronectin, 33 kD fragment, and peptide I. Radiolabeled cells were incubated for 30 min at 37°C in microtiter wells in the presence of increasing concentrations of purified IgG from rabbits immunized with peptide I as described in Materials and Methods. The wells were coated with 1μg of fibronectin (■), 2 μg of 33-kD fragment (○), or peptide I (△). The percent inhibition of cell adhesion was quantitated as: (1 minus [the number of cells bound in the presence of the inhibitor divided by the number of cells bound in the absence of the inhibitor]) multiplied by 100. Inhibition of cell adhesion in the presence of normal rabbit IgG was then subtracted at the corresponding IgG concentration. Each value represents the mean of three separate determinations, and the SEM was <5% in each case. Three separate experiments gave similar results.

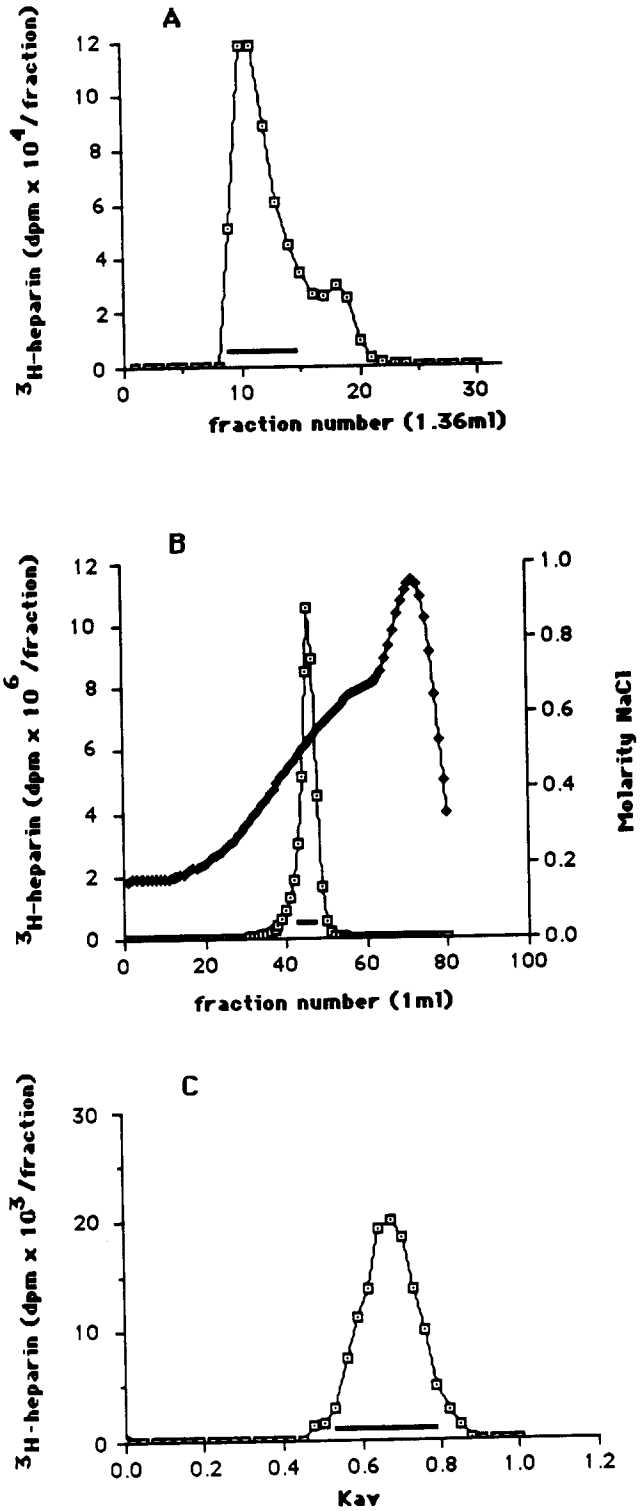

Figure 8. Purification of commercial [^{3}H]heparin. (*A*) Commercial [^{3}H]heparin was applied to and eluted from a Sephadex G-50 column as described in Materials and Methods. (*B*) The V_0 fractions (1.36 ml/fraction) were pooled as indicated by the bar, concentrated, and applied to an HPLC DEAE column equilibrated in 0.05 M Tris-HCL, pH 7.0, containing 6 M urea, 0.1 M NaCl, 0.2% CHAPS. The HPLC-DEAE column was eluted with the indicated gradient of NaCl (♦) and the radioactivity of each 1.0-ml fraction determined (⊡). (*C*) The entire peak comprising fractions indicated by the bar was pooled, concentrated, and applied to an analytical Sepharose CL-6B column equilibrated in 0.5 M sodium acetate containing 0.2% CHAPS. The peak fractions were pooled as indicated by the bar and used in the [^{3}H]heparin binding assays.

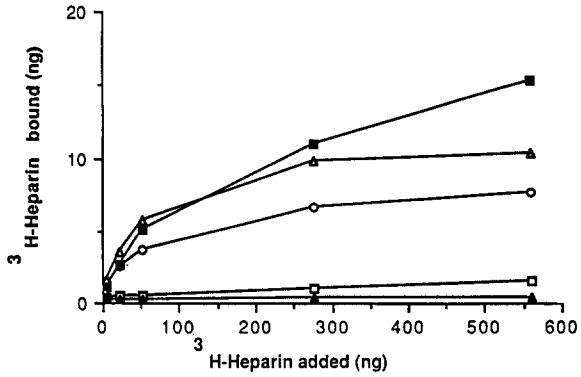

Figure 9. Binding of [^{3}H]heparin to substrata coated with various ligands. Substrata were coated with 4 μg of intact fibronectin (■), 10 μg of 33-kD fragment (○), 5 μg of peptides I (△) or CS1 (▲), or 200 μg of BSA (□) as described in Materials and Methods. The wells were then blocked with PBS/BSA, incubated for 2 h in the presence of the indicated concentrations of purified [^{3}H]heparin, and the amount of bound [^{3}H]heparin determined. The binding of [^{3}H]heparin in the presence of a 100-fold excess of unlabeled heparin was at background levels of radioactivity. Each value represents the mean of three separate determinations, and the SEM was <10% of the mean values in each case.

sentially the same extent. The capacity of fibronectin to bind [^{3}H]heparin was increased approximately twofold when the binding was performed in low (0.05 M) salt; however, no such increase was observed for the 33-kD fragment or peptide I. This is what would be expected if the amino terminal weak heparin binding domain of fibronectin (Smith and Furcht, 1982; McCarthy et al., 1986; see Fig. 1, domain I) exhibited activity at this lower salt concentration. Increasing the salt concentration above 0.15 M inhibited the binding of [^{3}H]-heparin to essentially the same extent on all three substrata. Minimal [^{3}H]heparin binding to each of these three ligands was observed in the presence of 0.25 M NaCl, with essentially background binding observed at salt concentrations higher than 0.25 M NaCl.

The ability of related polysaccharides to inhibit the binding of [^{3}H]heparin to intact fibronectin and peptide I was

Table I. Effect of Salt on the Binding of [^{3}H]Heparin to Fibronectin, 33-kD Fragment, or Peptide I

	Heparin bound (ng)‡			
Substratum*	0.05 M	0.15 M	0.25 M	0.35 M
Intact fibronectin	6.3	3.7	0.3	0.2
33-kD fragment	3.7	3.0	0.6	0.3
Peptide I	3.4	3.0	0.7	0.2
BSA	0.4	0.7	0.3	0.2

* Immulon 1-coated substrata were prepared by drying down 4 μg of intact fibronectin, or peptide I, 200 μg of BSA, and 10 μg of 33-kD fragment as described in Materials and Methods.

‡ The effect of the indicated salt concentrations on the binding of purified [^{3}H]heparin to each substratum was determined. The assay was performed using binding buffers that contained the indicated concentrations of NaCl, and each condition was washed with the same concentration of salt used in the assay before the determination of the bound [^{3}H]heparin. The bound radioactivity at the end of the assay was solubilized and determined as described and used to calculate the amount of heparin bound to the various substrata. Each well contained ~50 ng of heparin at the beginning of the assay. Values represent the means of triplicate determinations, with the SEs of the means <10% of mean values in all cases.

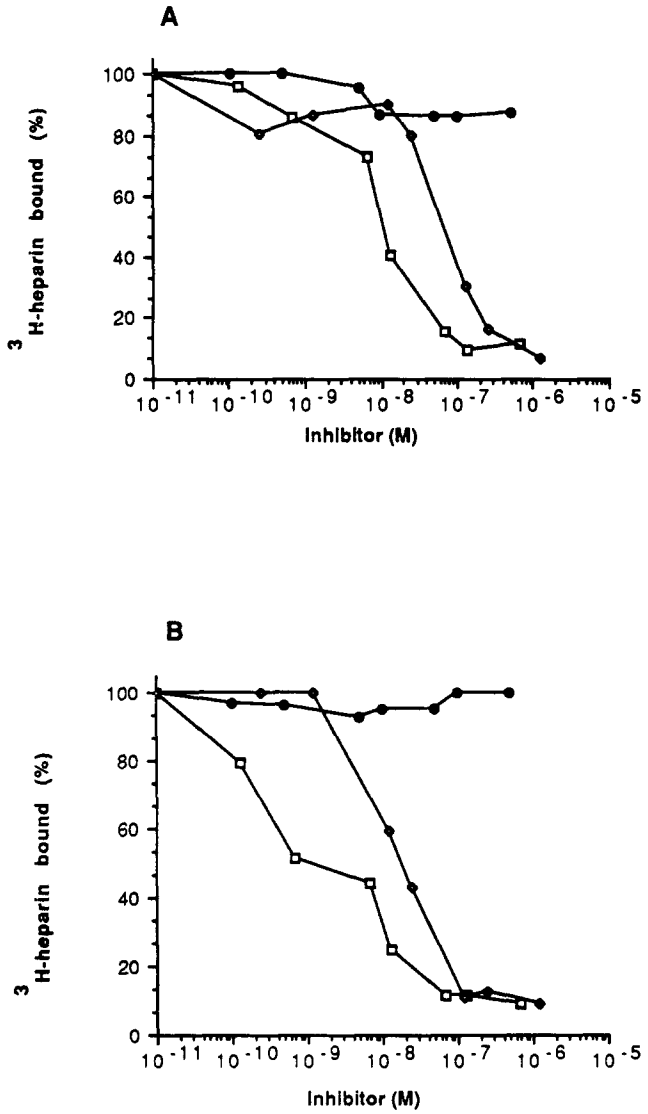

Figure 10. Inhibition of [^{3}H]heparin binding to intact fibronectin and peptide I by sulfated polysaccharides. Substrata coated with intact fibronectin (*A*) or peptide I (*B*) were prepared as described in Materials and Methods. Subsaturating levels of [^{3}H]heparin (50 ng/well) were mixed with the indicated concentrations of unlabeled heparin (□), dextran sulfate (◇), or chondroitin sulfate (●) and incubated in the wells for 2 h. The wells were then washed and the amount of bound [^{3}H]heparin was determined. Each value represents the mean of three separate determinations, and the SEM was <10% in each case.

also compared (Fig. 10). Unlabeled heparin was most effective at inhibiting [^{3}H]heparin binding to either substratum, producing a 50% inhibition at between 10^{-9} M (peptide I) and 10^{-8} M (fibronectin) competing heparin. Dextran sulfate was an order of magnitude less effective at inhibiting 50% of the binding of [^{3}H]heparin to either substratum. At high concentrations, however, dextran sulfate could virtually eliminate heparin binding to either ligand, suggesting that high concentrations of dextran sulfate could nonspecifically inhibit [^{3}H]heparin binding on the basis of charge. In contrast, less charged chondroitin-4 sulfate glycosaminoglycans were virtually ineffective at inhibiting the binding of [^{3}H]-heparin to peptide I or intact fibronectin, even at micromolar concentrations.

Finally, the ability of anti-peptide I IgG to inhibit the binding of [^{3}H]heparin to intact fibronectin was examined (Fig. 11). This IgG inhibited the binding of [^{3}H]heparin to intact fibronectin, in a concentration-dependent fashion. The highest concentration of IgG tested (500 μg/ml) inhibited ~60% of the [^{3}H]heparin binding to intact fibronectin. In contrast, normal rabbit immunoglobulin was much less effective at inhibiting [^{3}H]heparin (19% inhibition at 500 μg/ml, not shown).

Discussion

Our previous results were the initial ones that demonstrated that fibronectin contains RGDS-dependent and independent adhesion promoting activities (McCarthy et al., 1986, 1988*a*). A major RGDS-independent cell adhesion-promoting activity was first identified within an A-chain derived, carboxy-terminal 33-kD heparin-binding fragment of fibronectin (McCarthy et al., 1986) and others have observed similar results using a variety of normal and transformed cell types (Rogers et al., 1987; Mugnai et al., 1988; Wayner et al., 1989). These studies demonstrate that this fragment contains two cell adhesion-promoting domains that are localized within heparin binding peptide I (McCarthy et al., 1988*a*) and peptide CS1 (Humphries et al., 1987). Although peptides I and CS1 are both present within the 33-kD fragment (McCarthy et al., 1988*a*), the melanoma cell adhesion-promoting activity of these two synthetic peptides was shown to be distinct. First, cell adhesion to either peptide could not be cross-inhibited by the other peptide. Also, in contrast to peptide I, peptide CS1 failed to bind [^{3}H]heparin in a solid-phase binding assay. These results strongly suggest that peptides I and CS1 interact with distinct cell surface receptors, although interaction of both peptides with distinct sites on a common receptor cannot be ruled out.

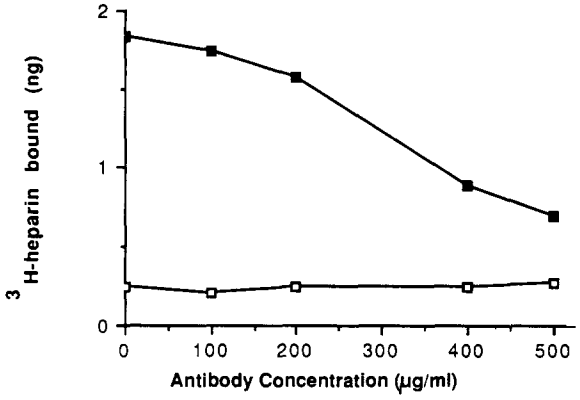

Figure 11. Effect of anti-peptide I IgG on [^{3}H]heparin binding to intact fibronectin. Substrata coated with 5 μg of intact fibronectin (■) or 200 μg of BSA (□) were preincubated for 30 min in the presence of the indicated concentrations of purified anti-peptide I antibodies in PBS/BSA. Each well then received subsaturating amounts of [^{3}H]heparin (~50 ng/well) and the plates were incubated for 2 h at 37°C. The wells were then washed and the amount of bound [^{3}H]heparin was determined. Each value represents the mean of three separate determinations, and the SEM was <10% in each case.

An additional distinction between peptides I and CS1 was the requirement (or not) for the peptides to be coupled to a larger carrier protein to express the full complement of cell adhesion- and spreading promoting activities. Whereas peptide I was fully active with respect to both criteria regardless of whether or not it was coupled, peptide CS1 required coupling to a larger carrier molecule in order to exhibit spreading activity. Such a requirement for coupling of this peptide has been previously noted by Humphries et al. (1986) in the original description of this peptide. Despite the requirement of coupling for spreading, uncoupled peptide CS1 was active at promoting cell adhesion on coated substrata. Whereas this difference could indicate the presence of separate adhesion and spreading promoting determinants on peptide CS1, which is relatively large, it is more likely that the difference represents changes in the conformation (and hence specific activity) of the peptide that has been bound by the two different means.

The observation that the cell adhesion–promoting activity exhibited by peptide I was active within the 33-kD fragment of fibronectin was supported by two independent lines of evidence. First, exogenous peptide I could inhibit cell adhesion on the 33-kD fragment of fibronectin although the inhibition achieved with this peptide was never complete. Secondly, antibodies generated against peptide I bound directly to the 33-kD fragment of fibronectin (by ELISA) and were effective at inhibiting cell adhesion to the 33-kD fragment of fibronectin. Whereas these antibodies could virtually eliminate cell adhesion to peptide I, the inhibitory effects on the 33-kD fragment were never complete, consistent with the hypothesis that multiple distinct cell adhesion promoting determinants exist on the 33-kD fragment. Interestingly, anti–peptide I antibodies had a limited effect on cell adhesion to intact fibronectin. This is consistent with our previous results (McCarthy et al., 1988*a*) and the results of others (Woods et al., 1986), which demonstrated that antibodies that inhibit cell adhesion to heparin binding fragments of fibronectin have a limited effect on the level of cell adhesion to intact fibronectin. However, such antibodies have been demonstrated to potentiate the effects of exogenous RGD-containing peptides (McCarthy et al., 1988*a*) or to disrupt focal adhesion formation by normal fibroblasts (Woods et al., 1986).

Anti–peptide I antibodies, which reacted positively by ELISA against intact fibronectin or the 33-kD fragment, were also extremely (60%) effective at inhibiting [^{3}H]heparin binding to intact fibronectin, indicating that peptide I represents a major heparin binding determinant on the carboxy-terminal heparin binding domain of intact fibronectin. The failure of these antibodies to completely inhibit heparin binding to intact fibronectin could relate, in part, to the contribution of other heparin binding determinants within this region of fibronectin (e.g., peptide II, which was not recognized by these antibodies; McCarthy et al., 1988*a*). This result further suggests that heparin binding to the carboxy-terminal region of fibronectin involves noncontiguous determinants within this region of the molecule. Multiple heparin-binding determinants have previously been proposed on other heparin binding proteins such as apolipoprotein B and vitronectin (Suzuki et al., 1985; Hirose et al., 1987; Cardin et al., 1989).

Peptide I was not as active on a molar basis as intact fibronectin at binding [^{3}H]heparin, requiring a 100-fold molar excess coating concentration compared with that used for fibronectin in order to achieve the same level of [^{3}H]heparin binding. Despite this difference in absolute activities, a relative comparison of the heparin binding activities of peptide I and intact fibronectin showed remarkable similarity between these two ligands. The heparin binding activities of these two ligands (and the 33-kD fragment) were equally susceptible to the effect of progressively increasing salt concentrations (at physiologic levels or above). Similarly, the 50% inhibitory dose of dextran sulfate was much less effective (one to two orders of magnitude) than unlabeled heparin at inhibiting [^{3}H]heparin binding to either of these two ligands. Chondroitin-4 sulfate (CS) was virtually ineffective in this regard, even at CS concentrations which were four orders of magnitude higher than the level of heparin that produced a 50% inhibition. Such specificity has previously been observed for heparin binding peptides from laminin (Charonis et al., 1988) and type IV collagen (Koliakos et al., 1989), although not all heparin-binding ligands show this same preference (Koliakos et al., 1989). This suggests, along with the antibody data, that the structural features of peptide I that are important for heparin-binding activity closely resemble those features of this sequence on intact fibronectin.

That peptide I-mediated cell adhesion could be distinguished from peptide CS1-mediated cell adhesion by several criteria suggests that the two peptides may mediate cell adhesion by interacting with distinct cell surface receptors, both of which are distinct from the well characterized RGD-dependent integrin interaction. Recent evidence has been presented which demonstrates that anti-β1 integrin antibodies can inhibit CS1-mediated adhesion of neural crest cells or peripheral neurons, indicating that CS1-mediated adhesion may involve cell surface integrins (Dufour et al., 1988; Humphries et al., 1988; Wayner et al., 1989), which are interacting by an RGD-independent mechanism. By contrast, the heparin-binding activity of peptide I argues strongly for a role of cell surface proteoglycans/glycosaminoglycans in the recognition of the active sequence(s) within this peptide. That peptide I promotes cell spreading as well as adhesion indicates that the melanoma cell surface receptor for this sequence interacts either directly or indirectly with the cellular cytoskeleton of these cells. Cell surface heparan sulfate and chondroitin sulfate proteoglycans have been identified with properties consistent with a cell surface localization, which include an ability to bind to hydrophobic affinity columns or to become inserted into liposomes (Kjellén et al., 1981; Woods et al., 1985; Lories et al., 1987; David et al., 1989). Putative transmembrane sequences have also been identified on the core proteins of several proteoglycans (Sant et al., 1984; Noonan et al., 1988; Saunders et al., 1989), suggesting that such macromolecules could be involved in peptide I-mediated melanoma cell adhesion. It will clearly be of interest to use peptide I to determine the role of cell surface–associated proteoglycans in mediating melanoma cell adhesion to this region of fibronectin.

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