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13. ABSTRACT (Maximum 200 words) Invasion and metastasis of breast cancer cells requires a cell-surface proteinase cascade in which the proteinase, plasmin, plays a prominent role. The tumor invasion proteinase cascade functions optimally only when plasmin is bound to the cell surface. Different cellular receptors may be responsible for plasmin-binding. The goal of this research program has been to identify macromolecules responsible for plasmin bindings in breast cancer cells and to characterize the function of these receptors. In the third year of this research program, we made substantial progress towards understanding the function of cell-surface cytoke- ratin-8 (CK8) as the major plasminogen receptor in three different breast cancer cell lines. Our studies have demonstrated that CK8 promotes plasminogen activation by tPA through the formation of a tetramolecular complex which may also involve CK18. Using genetic constructs, we characterized the binding sites for tPA and plasminogen in the cytoke- ratins and we have determined that these binding sites are non-identical. While CK8 serves as the principal binding site for plasminogen in MCF-7 cells, a separate macromolecule is apparently responsible for binding the plasminogen which serves as substrate for uPA in the protease cascade. We have also learned that highly aggressive breast cancer cell lines, which metastasize in animal model systems, do not express CK8 on the cell surface, probably due to the lack of desmosome structures. We have thus proposed a new model regarding plasminogen receptors and the tumor invasion proteinase cascade in breast cancer.			
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FOREWORD

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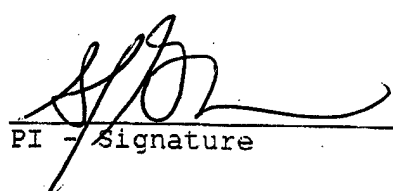
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Table of Contents:

Front Cover	1
SF 298 Report Documentation Page	2
Foreword	3
Table of Contents	4
Introduction	5
Body	5-8
Conclusions	8
References	9
Appendix	10

Introduction:

Cancer invasion and metastasis are promoted by proteinases which are organized on the cell surface by a series of cellular receptors. These proteinases form a cascade which culminates in the digestion of basement membrane and extracellular matrix proteins, allowing tumor cells to penetrate through tissue (1). At the top of the tumor invasion cascade is urokinase-plasminogen activator (uPA), a plasminogen activator which binds to a specific cellular receptor called uPAR (2,3). In breast cancer, cellular expression of uPA and uPAR has been correlated with an aggressive, malignant phenotype (4,5).

When uPA is bound to uPAR, the proteinase effectively activates cell associated plasminogen to form plasmin. Plasmin, in turn, digests glycoprotein components of the extracellular matrix and may activate other proteinases (6,7). A second plasminogen activator, tissue-type plasminogen activator (tPA), also binds to tumor cell surfaces and may substitute for uPA in certain circumstances (8).

Migrating cells show the capacity to polarize the tumor invasion proteinase cascade to the leading edge of cellular migration (1). Thus, the cell may selectively digest structural proteins in the direction of migration. When we began our work, the nature of the cellular binding sites for plasminogen in breast cancer cells was unknown. Plasminogen binding sites have been described in other cell types, but in most cases, subsequent studies demonstrated that these binding sites are not responsible for a substantial fraction of the plasminogen binding capacity (9-12). By contrast, a growing body of literature supports the hypothesis that plasminogen binding to the cell surface is **essential** for the optimal function of the tumor invasion proteinase cascade (13).

The major goal of this research program has been to identify and characterize plasminogen binding sites in breast cancer cells. We consider this binding site to be an exciting and unexplored target for potential disruption of the tumor invasion proteinase cascade. The body of literature, outlined above, supports the selection of this interaction for investigation.

Body:

In the first two years of this research program, we conducted experiments demonstrating that the intermediate filament protein, cytokeratin 8 (CK8), or a CK8-like protein, is expressed on the surfaces of a number of breast cancer cell lines, including MCF-7 cells and BT-20 cells. This was an unexpected result since cytokeratins do not contain transmembrane domains. It was fairly well accepted that cytokeratins form an insoluble lattice which extends from the nucleus to the interior surface of the plasma membrane. Our original publications regarding cell-surface cytokeratin 8 are included in the appendix (reprints of manuscripts in *J. Cell Science* and *J. Biol. Chem.*) for completeness; however, I will point out that the content of these papers was reviewed in a previous

report to the DAMD.

The presence of CK8 on the surfaces of breast cancer cell lines was extremely important to us since our studies demonstrated that cell-surface CK8 is the primary binding protein for plasminogen in these cell lines. When we blocked cell-surface CK8 with monoclonal antibody 1E8, which we raised in our laboratory, plasminogen binding to the surfaces of MCF-7 and BT20 cells was substantially reduced. We also neutralized the ability of the breast cancer cells to promote the activation of plasminogen by tissue-type plasminogen activator (tPA). These studies, which were described in detail in my previous report, are also described in the three published manuscripts included with this report. Since the time that we originally published our results regarding cell-surface CK8, we are excited to see that many other laboratories have confirmed and extended our observations. Ditzel et al. (14) also detected cytokeratins on the surfaces of carcinoma cells. These investigators suggested that cytokeratins 8 and 18 may represent new targets for immunoconjugates used in cancer therapy. Wells et al. (15) reported that cytokeratin 18 is expressed on hepatocyte plasma membranes and serves as a major receptor for thrombin-antithrombin complexes. Finally, it has also been reported that cytokeratins on the surfaces of cells may play a role in the immobilization of high molecular weight kininogen (16).

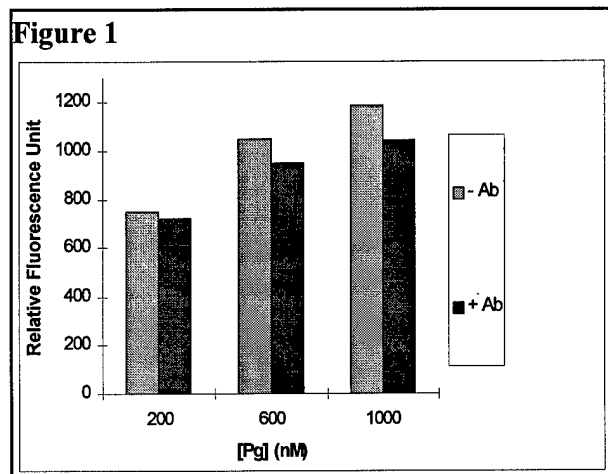
In the time period between October 1996 and October 1997, our research took two major directions. The first was highly successful and involved the use of genetic constructs to further elucidate the interactions of the cytokeratins with plasminogen and tPA. We chose to prepare genetic constructs since purified cytokeratins are highly insoluble and thus can be subjected to only limited biochemical analysis. Our first construct encoded a GST-fusion protein containing 174 amino acids from the C-terminus of CK8 (CK8f). The second construct was identical to the first except that the C-terminal lysine, which we have previously demonstrated to be critical for plasminogen binding, was mutated to glutamine (CK8f_{K483→Q}). The third construct encoded 134 amino acids from the C-terminus of wild type CK18. A detailed analysis of the experiments performed with these constructs, including eight figures, is presented in a manuscript which is submitted for publication (included in Appendix). Our studies demonstrated that plasminogen binding activity is unique to CK8 and highly dependent on the C-terminal lysine residue. Unlike other plasminogen-binding proteins, CK8 was unique in that mutation of the C-terminal lysine inhibited but did not completely preclude plasminogen binding. Thus, we concluded that CK8 contains amino acids adjacent to the C-terminus which contribute to the plasminogen-binding interaction in addition to the C-terminal lysine.

In contrast with plasminogen, tPA bound not only to CK8 but to CK18. The C-terminal lysine was not involved in this interaction. Thus, we were able to conclude that the plasminogen and tPA binding sites in the cytokeratins are non-identical. However, plasminogen and tPA cross-competed for binding to CK8 (see figure 4 in the paper presented in the Appendix). As expected, plasminogen did not compete with tPA for binding to CK18. These results suggest that although the tPA and plasminogen binding sites in CK8 are non-identical, they are overlapping. Thus, in order to organize an activation complex which includes cofactor, tPA, and plasminogen, two molecules of cytokeratin are minimally necessary. In other words, the minimum plasminogen activation unit is a tetramolecular complex in which the plasminogen and tPA are brought into close juxtaposition by two polymerized

molecules of cytokeratin. This model is described in detail in the discussion of the accompanying manuscript.

As a second direction, we have attempted to expand our understanding of the function of the cytokeratins in breast cancer invasion. Our first objective was to characterize the function of CK8 as a plasminogen binding protein for the uPA-mediated tumor invasion protease cascade. As outlined

in the original grant application, numerous clinical studies have strongly implicated both uPA and its receptor, uPAR, as negative prognostic factors in breast cancer. There is no evidence to suggest that tPA expression by breast cancer cells is correlated with a negative prognosis.

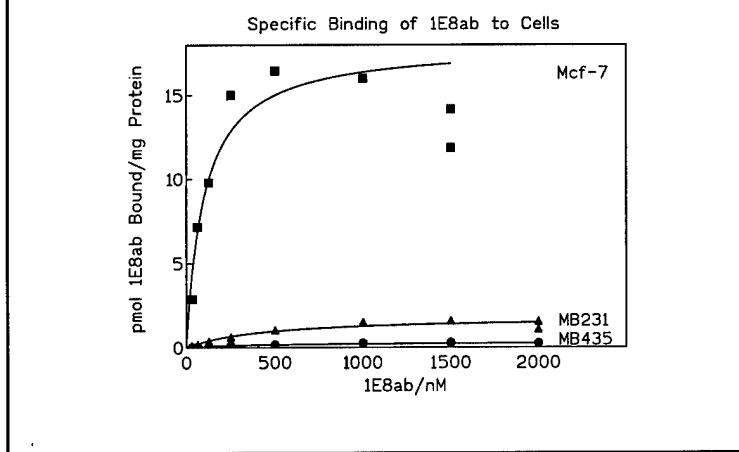


Our studies with uPA have led us to conclude that the pool of cell-surface plasminogen which serves as substrate for uPAR-associated uPA is not the CK8-associated plasminogen. A representative study is shown in Figure 1. In this study, we pretreated MCF-7 cells with monoclonal antibody 1E8 (4 mM).

This antibody effectively neutralizes the ability of cell-surface CK8 to bind plasminogen. Furthermore, antibody 1E8 inhibits plasminogen activation by tPA by greater than 75%. As shown in Figure 1, antibody 1E8 had little or no effect on uPA-mediated plasminogen activation on the surfaces of MCF-7 cells. This result was consistent, irrespective of the initial saturation of cell-surface CK8 with plasminogen (which was altered by varying the initial plasminogen concentration added to the culture medium). This intriguing result raises new questions regarding the diversity of plasminogen binding proteins on the cell surface. The function of cytokeratins 8 and 18 as tPA binding proteins and the importance of antibody 1E8 in blocking tPA-mediated plasminogen activation are consistent with a single model. However, the results presented in Figure 1 suggest that some other plasminogen binding protein, which contributes minimally to the total binding capacity of the breast cancer cells, must function to bind plasminogen in the uPA-mediated protease cascade.

In this project year, we also completed a series of experiments with the breast cancer cell lines, MDA-MB-231 and the MDA-MB-435. We chose to analyze these two cell lines, since unlike the MCF-7 and BT20 cells, these breast cancer cell lines are invasive *in vivo*. Thus, by studying these cell lines, we could set the ground work for future *in vivo* studies. Initially, we evaluated the binding of ^{125}I -plasminogen to the MDA-MB-231 and MDA-MB-435 cells. Although the affinity (K_D) of plasminogen for binding sites in these two tumor cell lines was comparable to that observed with the MCF-7 cells (about 1 μM), the MDA-MB-231 and MDA-MB-435 cells had substantially lower binding capacities (decreased by approximately 1-2 orders of magnitude compared with the MCF-7 cells (results not shown)). This was an unexpected finding since one would intrinsically speculate that there might be more protease binding sites on a more aggressive tumor cell line. Figure 2 shows

Figure 2



experiments in which we examined the specific binding of ^{125}I -labeled monoclonal antibody 1E8 to the MDA-MB-231 and MDA-MB-435 cells. As demonstrated in a previous study, this antibody binds in a specific and saturable manner to MCF-7 and BT20 cells in culture. The binding studies were performed at 4°C to avoid any complications arising from endocytosis, as previously reported (14). However, as shown in the figure, monoclonal antibody 1E8 did not bind to the two highly aggressive breast cancer cell lines. Furthermore, in studies that are

not shown, monoclonal antibody 1E8 did not inhibit plasminogen binding to these cell lines or plasminogen activation. Thus, we conclude that cytokeratin 8 is not expressed on the surfaces of these more aggressive breast cancer cell lines. At the recent meeting in Washington, D.C. (Era of Hope), we learned in discussion with other investigators, that the MDA-MB-231 and MDA-MB-435 cells may not form desmosomes or hemidesmosomes. Since these cell membrane structures represent the regions of the plasma membrane where cytokeratins make contact, we hypothesize that the cytokeratins penetrate through the plasma membrane in the desmosomal regions.

Based on our studies with the more aggressive breast cancer cell lines and with urokinase, we have revised our original model for the function of cytokeratin 8 in organizing the tumor invasion proteinase cascade. We now hypothesize that only the better differentiated breast cancer cells may in fact express cell-surface cytokeratin 8. In these cell types, the level of cytokeratin 8 on the cell surfaces is extremely high and can potentially serve as a sink for the majority of the plasminogen in the pericellular spaces. As a result, less plasminogen may be available to bind to alternative plasminogen binding sites on the cell surface which are involved in the uPA-mediated tumor invasion cascade. We are currently testing this hypothesis.

Conclusions:

1. Cytokeratin 8 serves as the major plasminogen binding protein in MCF-7 and BT20 breast cancer cells.
2. More aggressive breast cancer cells, which have less organized intermediate filament-based cytoskeletons, do not utilize cytokeratin-8 as the major plasminogen receptor.
3. tPA-mediated plasminogen activation is promoted by cytokeratins while uPA-mediated plasminogen activation is not.

4. Of the cell surface cytokeratin, only CK8 binds plasminogen while both CK8 and CK18 bind tPA.
5. The plasminogen and tPA binding sites in cytokeratin 8 are non-identical, but overlapping.
6. The minimal activation complex for tPA-mediated plasminogen activation is a tetramolecular complex involving tPA, plasminogen and at least two monomeric units of cytokeratin.

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A cytokeratin 8-like protein with plasminogen-binding activity is present on the external surfaces of hepatocytes, HepG2 cells and breast carcinoma cell lines

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SUMMARY

Plasminogen binding to cell surfaces may be important for tumor invasion and other processes that involve cellular migration. In this investigation, the principal plasminogen-binding protein was identified in the plasma membrane fraction of rat hepatocytes. The protein had an apparent mass of 59 kDa, was insoluble in a spectrum of detergents, and was identical to cytokeratin 8 (CK 8) as determined by sequence analysis of nine amino acids at the N terminus of two cyanogen bromide fragments. The 59 kDa protein bound CK 8-specific antibody in western blot analyses. These studies demonstrate that CK 8 or a CK 8-like protein binds plasminogen. Given this newly determined and potentially important CK 8 function, immunofluorescence and immunoelectron microscopy studies were performed to determine whether CK 8 may be present on the external surfaces of unpermeabilized, viable hepatocytes. All of the cells in each preparation were immunopositive with two

separate CK 8-specific antibodies. A punctate pattern of immunofluorescence was detected on the cell surface with approximately even intensity from cell to cell. By immunoelectron microscopy, CK 8 was preferentially associated with microvilli. In order to determine whether other epithelial cells express cell-surface CK 8, immunofluorescence and immunoelectron microscopy studies were performed with HepG2 hepatocellular carcinoma cells and with BT20 and MCF-7 breast carcinoma cells. The pattern of antigen expression was equivalent with each cell type and comparable to that observed with hepatocytes. These studies support the hypothesis that CK 8 is associated with the external cell surface where it may express important proteinase receptor function.

Key words: plasminogen, cytokeratin, plasma membrane, intermediate filament

INTRODUCTION

Plasmin is a serine proteinase that plays a central role in fibrinolysis. At the cell surface and in the pericellular spaces, plasmin cleaves many substrates other than fibrin, including: glycoprotein components of the extracellular matrix (Liotta et al., 1981), zymogen forms of certain matrix metalloproteinases (He et al., 1989), glycoprotein IIIa (Pasche et al., 1994), growth factor precursors such as latent transforming growth factor- β (TGF- β) (Lyons et al., 1988), insulin-like growth factor-binding protein (Campbell et al., 1992), interferon- γ (Gonias et al., 1989b), the thrombin receptor (Turner et al., 1994), and the type III TGF- β receptor/betaglycan (LaMarre et al., 1994). These enzyme-substrate reactions suggest multiple mechanisms by which plasmin may regulate cellular growth, differentiation and cellular migration.

The diverse continuum of plasmin substrates emphasizes the importance of regulating this proteinase within the pericellular spaces. Plasmin regulation is accomplished at three levels. The first is activation, which involves the proteolytic conversion of

single-chain plasminogen into the active two-chain structure (Ponting et al., 1992). Once activated, plasmin is regulated by proteinase inhibitors, including α_2 -antiplasmin and α_2 -macroglobulin (Ellis and Dano, 1992; Gonias, 1992; Vassalli et al., 1991). Plasmin is also regulated spatially by noncovalent binding interactions that localize and concentrate the proteinase (and zymogen) in specific microenvironments. Reversible plasmin(ogen) binding to cell surfaces, fibrin clots and specific extracellular matrix proteins is mediated by five homologous plasmin(ogen) kringle domains (Ponting et al., 1992). The kringle domains have binding sites with affinity for lysine residues in other proteins. Association of plasminogen with many proteins depends on the relatively high-affinity interaction of the kringle-1 (K1) domain with a carboxy-terminal lysine residue (Christensen, 1985; Fleury and Anglés-Cano, 1991; Miles et al., 1991).

Plasmin(ogen)-binding proteins, including those present on cell surfaces, not only localize plasmin near potential substrates, but also significantly alter the kinetics of plasminogen activation and plasmin inhibition (Ellis and Dano, 1992;

Gonias, 1992). Therefore, understanding the spectrum of physiologically significant plasminogen-binding proteins is important. Nucleated mammalian cells, including endothelial cells (Hajjar et al., 1986), monocytes/macrophages (Plow et al., 1986), hepatocytes (Gonias et al., 1989a) and tumor cells (Burtin and Fondaneche, 1988; Correc et al., 1990; Hall et al., 1990) express specific plasmin(ogen)-binding sites. The binding affinity is typically low ($K_d \sim 1.0 \mu\text{M}$); however, the capacity is high (10^5 - 10^7 sites per cell). Specially plasminogen binding to all cell types can be completely inhibited by lysine analogues such as ϵ -amino caproic acid (EACA) (Hajjar et al., 1986; Gonias et al., 1989a), confirming the kringle domain-dependency of these interactions.

Plasminogen-cellular interactions may be mediated by different cellular proteins. α -Enolase was identified as a candidate plasminogen receptor in U937 monocytes (Miles et al., 1991). Although α -enolase is primarily an intracellular protein, FACS analysis was used to demonstrate that this antigen is present on cell surfaces. Annexin-2 is another primarily intracellular protein that may be found in association with the external surfaces of endothelial cells where it functions as a receptor for plasminogen and tissue-type plasminogen activator (Hajjar et al., 1994). Amphotericin is a candidate plasminogen receptor in developing brain (Parkkinen and Rauvala, 1991). It has also been shown that purified Heymann Nephritis autoantigen (gp330) binds plasminogen (Kanas and Makker, 1991).

The present study was undertaken to identify major plasminogen binding proteins in hepatocytes. Similar analyses of epithelial cells have not been previously reported. Our results demonstrate that cytokeratin 8 (CK 8) or a CK 8-like protein is the major plasminogen binding protein in the plasma membrane fraction of rat hepatocytes. CK 8 is a basic-neutral intermediate filament protein, unique amongst cytokeratins in that it has a C-terminal lysine residue (Morita et al., 1988). CK 8 extends from the nucleus to the plasma membrane where it has extensive interactions with the internal leaflet and with various membrane-associated structures, including desmosomes and hemidesmosomes (Garrod, 1993; Owaribe et al., 1991). Epithelial cells, and especially carcinoma cells, secrete CK 8 or CK 8 fragments *in vivo*; these fragments are a major component of the long-recognized body-fluid complex, Tissue Polypeptide Antigen (TPA) (Leube et al., 1986; Weber et al., 1984). It has been proposed that CK 8 is also present on the external surfaces of epithelial cells (Godfroid et al., 1991; Donald et al., 1991). At least three mechanisms might hypothetically account for this. First, the CK 8 may penetrate through the plasma membrane as part of a multiprotein complex, despite the lack of a transmembrane domain. Second, CK 8 that is secreted by cells may tightly associate with the external surface of the plasma membrane (Riopel et al., 1993). Finally, since CK 8 covalently binds to plasma membrane lipids (Asch et al., 1993), it is conceivable that these complexes are translocated to the outer membrane leaflet.

The previous studies demonstrating cell-surface CK 8 have been contested on the basis that the experimental techniques utilized might detect primarily damaged or permeabilized cells (Riopel et al., 1993). Given the new function of CK 8 demonstrated here, we considered it important to re-evaluate the question of CK 8 exposure on cell surfaces. Therefore, in the second part of this study, immunofluorescence microscopy and

immunoelectron microscopy experiments were performed. These studies detected, for the first time, CK 8 or a CK 8-like protein on the external surfaces of rat hepatocytes and HepG2 hepatocellular carcinoma cells. We also present a series of studies confirming the earlier, contested work regarding the presence of CK 8 on the external surfaces of breast carcinoma cells.

MATERIALS AND METHODS

Materials

Na^{125}I was from Amersham International (Arlington Heights, IL). Aprotinin, chloramine T, EACA, phenylmethyl-sulfonyl fluoride (PMSF), bovine serum albumin (BSA), sodium deoxycholate and fetal bovine serum (FBS) were purchased from Sigma (St Louis, MO). Leupeptin, *L-trans*-epoxysuccinyl-leucylamido(4-guanidino)butane (E-64), and collagenase D were purchased from Boehringer Mannheim. Williams E medium and Earle's balanced salt solution (EBSS) were from Gibco Laboratories (St. Lawrence, MA). D-Val-L-Leu-L-Lys *p*-nitroanilide (S-2251) was from Kabi Vitrum (Stockholm, Sweden).

Murine monoclonal antibody PCK-26, which recognizes CK 5, 6, and 8, and murine monoclonal antibody M20, which is specific for CK 8, were purchased from Sigma. The hybridoma, UCD/AB 6.01, was obtained from ATCC and expanded in ascites using IRCF₁ mice (Hilltop Labs, Scottsdale, PA). AB 6.01 was purified from the ascites by Protein A-Sepharose chromatography. This antibody is specific for CK 8 but cross-reacts slightly with CK 18 (Chan et al., 1985). In our western blot analyses of purified rat hepatocyte CK, performed as previously described (Wolf et al., 1992), only CK 8 was detected by AB 6.01 (results not shown). A monoclonal IgG₁ specific for GTPase activating protein (p120-GAP) was kindly provided as a gift by Dr Sarah Parsons (University of Virginia).

Cell culture

All cell lines were obtained from ATCC. The human hepatocellular carcinoma cell line, HepG2 (Aden et al., 1979), was cultured in MEM supplemented with 10% FBS and 2 mM glutamine. The human breast carcinoma cell line, BT20 (Lastargues and Ozzello, 1958), was cultured in RPMI 1650 with 10% FBS. MCF-7 (Soule et al., 1973) breast carcinoma cells were cultured in Eagle's minimum essential medium (EMEM) supplemented with 10% FBS, 10 $\mu\text{g}/\text{ml}$ insulin, and 2 mM glutamine.

Hepatocytes were isolated from 250-400 g Sprague-Dawley rats (male or female), using the well-described two-step perfusion method (Berry and Friends, 1969; Gonias et al., 1989a). The rats were purchased from Hilltop Laboratories. The hepatic cells were released into Williams E medium containing 10% FBS. The preparations were enriched in hepatocytes by centrifugation so that non-parenchymal cells represented less than 2% of the final populations. Adherent hepatocyte cultures were greater than 98% viable as determined by trypan blue exclusion 2 hours after isolation.

Purified plasminogen and plasminogen-Sepharose

Plasminogen was purified from human plasma by affinity chromatography on lysine-Sepharose (Deutsch and Mertz, 1970). A linear gradient of EACA (0 to 15 mM) was used to elute the plasminogen. Final preparations contained mixtures of the two major glycoforms but were free of detectable plasmin, as determined by SDS-PAGE and S-2251 hydrolysis. Purified plasminogen (100 mg) was coupled to 10 g of CNBr-activated Sepharose CL-4B (Porath et al., 1973). Approximately 60% of the plasminogen bound to the resin.

Plasminogen binding to cells in culture

Isolated rat hepatocytes were plated in collagen-coated 12-well or 24-

well plates at a density of 500,000 cells/ml and cultured in Williams E medium with 10% FBS. After 2 hours, the cultures were washed three times with EBSS, 10 mM Hepes, 0.1% BSA (w/v), pH 7.4 (EHB-buffer). Plasminogen was radioiodinated to a specific activity of 1-2 $\mu\text{Ci}/\mu\text{g}$ with Iodobeads (Hall et al., 1990) or chloramine-T (Miles and Plow, 1985). The ^{125}I -plasminogen was then incubated with the hepatocyte cultures in EHB and aprotinin (70 $\mu\text{g}/\text{ml}$) for 4 hours at 4°C. EACA (10 mM) was added to some wells. EACA and excess nonradiolabeled plasminogen are equally effective in inhibiting specific ^{125}I -plasminogen binding to cells in culture (Hajjar et al., 1986; Gonias et al., 1989a). ^{125}I -Plasminogen-binding experiments were terminated by washing the cultures 3 times with EHB. The cells were then lysed overnight in 0.1 M NaOH/1% SDS (w/v). Radioactivity in the lysates was determined in a gamma counter. An identical procedure was used to characterize plasminogen binding to HepG2 or breast carcinoma cells.

Plasma membrane preparation

Plasma membrane-enriched fractions of isolated hepatocytes were prepared according to the method of Fleischer and Kervina (1986) as modified by Wolf et al. (1992). All fractionation steps were performed in medium supplemented with 1 mM PMSF, 70 $\mu\text{g}/\text{ml}$ aprotinin, 30 $\mu\text{g}/\text{ml}$ leupeptin, 0.2 $\mu\text{g}/\text{ml}$ E-64, and 1 mM EDTA. The complete procedure yielded subcellular fractions enriched in nuclei (N), cytoplasm (C), mitochondria (M), and plasma membranes (P). Intermediate filament proteins are typically recovered in the P and N fractions (Hubbard and Ma, 1983).

SDS-PAGE and ligand blotting

Whole-cell homogenates, subcellular fractions, and purified proteins were subjected to SDS-PAGE (Laemmli, 1970). Resolved proteins were electrotransferred to polyvinylidene difluoride (PVDF) membranes (Millipore) using a Hoefer Transphor apparatus (2 hours, 0.5 amp). The membranes were then stained with Coomassie Blue R250 (Bio-Rad, CA) or blocked with 5% nonfat dried milk in 20 mM sodium phosphate, 150 mM NaCl, pH 7.4 (PBS), for ligand blotting or western blot analysis. To insure complete transfer, the original gel slab was stained with Coomassie Blue R250 as well.

Blocked PVDF membranes were rinsed twice with PBS and 0.1% (v/v) Tween-20 (PBS-T). ^{125}I -Plasminogen (10-20 nM) was then incubated with the membranes in PBS-T and 70 $\mu\text{g}/\text{ml}$ aprotinin for 45 minutes. The blots were rinsed 3 times for 15 minutes in PBS-T, dried and autoradiographed. In control experiments, ^{125}I -plasminogen was incubated with the PVDF membranes in the presence of EACA.

Plasminogen-affinity chromatography

Enriched plasma membranes (P fraction) were solubilized in 10 mM sodium deoxycholate, pH 8.4, for 2 hours at 4°C and then subjected to centrifugation for 15 minutes at $10^5 g$ in a Beckman airfuge. The insoluble pellet and the supernatant were analyzed by SDS-PAGE and ^{125}I -plasminogen-ligand blotting. The detergent-insoluble pellet was extracted with 6 M urea for 4 hours at 25°C and then dialyzed against 10 mM sodium deoxycholate. The resulting solution and the original detergent-soluble portion of the P-fraction were separately subjected to affinity chromatography on plasminogen-Sepharose. Associated proteins were eluted from plasminogen-Sepharose with 15 mM EACA in 10 mM sodium deoxycholate. Fractions were analyzed by SDS-PAGE with silver staining.

Micro-sequence analysis of the major plasminogen-binding protein

The major plasminogen-binding protein was eluted from PVDF and subjected to amino-terminal sequence analysis using an Applied Biosystems 470A Gas-Phase Sequencer equipped with a model 120A on-line analyzer. Since initial analysis suggested a blocked amino terminus, the binding protein was treated with 150 mM cyanogen bromide (CNBr) in 70% formic acid while adherent to PVDF.

Fragments were eluted with 1% (v/v) Triton X-100, 2% SDS, 50 mM Tris, pH 9.5, and then re-subjected to SDS-PAGE and electroblotting. New products were identified by Coomassie staining and subjected to amino-terminal sequence analysis. Results were compared with known sequences in GenBank using the Fasta Program (Pearson, 1994).

Immunofluorescence microscopy

Hepatocytes were adhered to collagen-coated 30 mm glass coverslips for 2 hours at 37°C and then studied immediately in immunofluorescence microscopy experiments. HepG2, BT20, and MCF-7 cells were cultured on coverslips for at least 48 hours. All cultures were washed with EHB buffer and incubated with various primary antibodies at 1/100-1/500 dilution in EHB for 2 hours at 4°C. The cells were then washed three times with EHB, incubated with FITC-labelled goat anti-mouse IgG (1/1000 dilution) for 2 hours at 4°C, rinsed three times again, and fixed in 3.7% paraformaldehyde or freshly prepared, ice-cold buffered-formaldehyde. Cellular immunofluorescence was imaged using an Olympus 3H2 Microscope with a dual wavelength cube. In control experiments, mouse nonimmune IgG was substituted for primary antibody or primary antibody was omitted.

Electron microscopy

Primary hepatocytes, breast carcinoma cells, and HepG2 cells were cultured on 10 mm plastic coverslips, as described for the immunofluorescence microscopy experiments. The cells were brought to 4°C and incubated with primary antibodies for 1 hour. At this point, the cells were incubated with either Protein A adsorbed to colloidal gold (100 Å) or anti-mouse IgG adsorbed to colloidal gold (100 Å) for 2 hours at 4°C. The cells were fixed with 2% osmium tetroxide in 0.1 M sodium cacodylate, pH 7.5, for 15 minutes. This fixative rapidly reacts with the lipid in plasma membranes and limits plasma membrane vesiculation (Hasty and Hay, 1978). After washing with PBS, the cells were further fixed with 2% paraformaldehyde/2% glutaraldehyde in 0.1 M sodium cacodylate, pH 7.5, for 8 hours at 4°C. The cells were then serially dehydrated in acetone and embedded in EPON 812 for polymerization at 60°C overnight. Embedded coverslips were thin-sectioned on-side. Sections were transferred to 150 mesh nickel grids and viewed on a Zeiss 902 electron microscope.

RESULTS

Plasminogen binding to cells in culture

In initial studies, we confirmed that hepatocytes in primary culture, HepG2, BT20, and MCF-7 cells bind plasminogen specifically. As expected, EACA displaced greater than 80% of the binding through the entire ^{125}I -plasminogen concentration range with each cell type. Scatchard transformations were linear with correlation coefficients of 0.90-0.98 (not shown). K_d and B_{max} values were derived assuming a single- K_d model (Table 1) and are consistent with previously reported studies of plasminogen binding to cells in culture (as reviewed above).

Characterization of plasminogen-binding proteins in the hepatocyte P-fraction

Plasminogen binds specifically to a number of cellular

Table 1. Specific binding parameters for the interaction of ^{125}I -plasminogen with cells in culture

Cell type	K_d (μM)	B_{max} (per cell)
Rat hepatocytes	0.75($\pm$ 0.1)	9.7($\pm$ 0.7) $\times 10^6$
HepG2	1.83($\pm$ 0.6)	4.3($\pm$ 1.0) $\times 10^6$
BT20	1.05($\pm$ 0.3)	5.9($\pm$ 1.0) $\times 10^6$
MCF-7	0.90($\pm$ 0.3)	1.9($\pm$ 0.4) $\times 10^6$

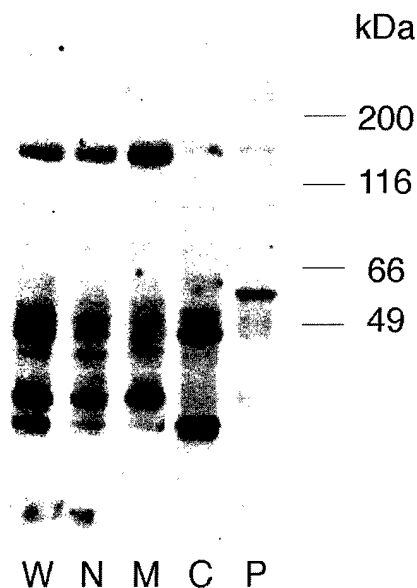


Fig. 1. ^{125}I -Plasminogen ligand blot of rat hepatocyte subcellular fractions. Lanes are labeled as follows: W, whole cell homogenate; N, nuclear fraction; M, mitochondrial fraction; C, cytoplasmic fraction; P, plasma membrane fraction. Each subcellular fraction has a unique set of plasminogen-binding proteins. The major plasminogen-binding species in the P fraction is the 59 kDa protein.

proteins, including some that are intracellular and not available unless the cell is permeabilized. To identify plasminogen-binding proteins that may be significant in intact cells, hepatocytes were subjected to subcellular fractionation. Plasminogen-binding proteins in each fraction were compared by ^{125}I -plasminogen ligand blotting. Fig. 1 shows a representative ligand blot in which equal amounts of protein (100 μg) from the various subcellular fractions were compared. Each subcellular fraction demonstrated a distinct and consistent fingerprint of plasminogen-binding proteins. The primary plasminogen-binding protein in the P-fraction had a mass of 59 kDa. ^{125}I -Plasminogen binding to this band was completely inhibited by a 100-fold molar excess of nonradiolabeled plasminogen or 15 mM EACA (results not shown).

The 59 kDa plasminogen-binding protein was not detected in the M or C fractions, in five separate experiments. In whole cell homogenates and N-fractions, the 59 kDa protein either was detected only with prolonged autoradiograph exposure time (as was the case for the preparation shown in Fig. 1) or was present as a distinct but minor band compared with other plasminogen-binding species (as observed in other experiments not shown). These results suggest any of the following possibilities: (i) the 59 kDa protein is selectively recovered in the P-fraction; (ii) the plasminogen-binding activity of the 59 kDa protein is less stable in other fractions; and/or (iii) the other subcellular fractions contain a higher proportion of other plasminogen-binding proteins that are excluded from the P-fraction.

Characterization of the 59 kDa protein

The P-fraction was treated with various detergents, including 1% Triton X-100, 25 mM CHAPS, 35 mM β -D octylglucoside, and 10 mM sodium deoxycholate. Detergent-soluble and

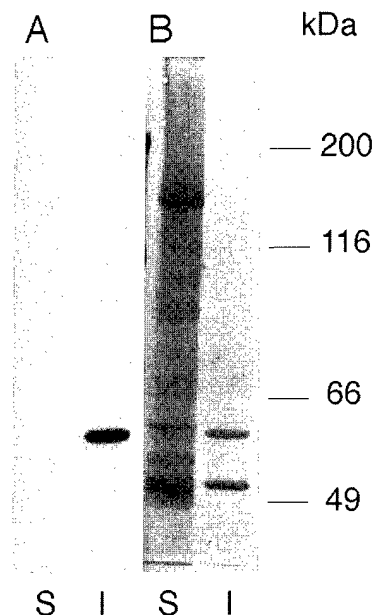


Fig. 2. ^{125}I -Plasminogen ligand blot and Coomassie-staining of detergent extracts of rat hepatocyte plasma membranes. (A) ^{125}I -plasminogen ligand blot of the detergent-soluble (S) and insoluble (I) fractions of the plasma membrane preparation. The detergent was 10 mM sodium deoxycholate. (B) Coomassie-stained blot of the same 'S' and 'I' fractions. The majority of the P-fraction is soluble in sodium deoxycholate. Two major bands remain in the detergent-insoluble fraction, including the 59 kDa plasminogen-binding protein.

-insoluble fractions were incubated in SDS at 95°C for 5 minutes and subjected to SDS-PAGE and ^{125}I -plasminogen ligand blotting. Each of the detergents solubilized the majority of the P-fraction proteins; however, the 59 kDa protein remained in the detergent-insoluble fraction. Fig. 2 shows a representative solubilization experiment with 10 mM sodium deoxycholate. In this experiment, 100 μg of P-fraction were incubated with detergent for 2 hours and then subjected to centrifugation at $10^5 g$. The entire contents of the pellet (I) and supernatant (S) were subjected to SDS-PAGE so that the amount of each protein in the gel would approximate the proportion of that protein in the original P-fraction. As shown in the Coomassie-stained PVDF blot (B), the sodium deoxycholate-insoluble fraction contained two major proteins. One of these proteins was the 59 kDa species; this component was the only major ^{125}I -plasminogen-binding protein identified in either detergent solubilization fraction (A). The detergent-soluble fraction included a minor ^{125}I -plasminogen-binding species with an apparent mass of 150 kDa; this species was barely visible in the ligand blot without prolonged autoradiograph exposure time. An equivalently sized species was also apparent in the ligand blot of intact P-fraction shown in Fig. 1.

In ^{125}I -plasminogen ligand blotting experiments, P-fraction components were exposed to SDS. Therefore, we considered the possibility that the P-fraction contains plasminogen-binding proteins that are inactivated by SDS. In eight separate experiments, 5–15 mg of P-fraction were solubilized with the various detergents listed above. The detergent-soluble fractions were subjected to plasminogen-affinity chromato-

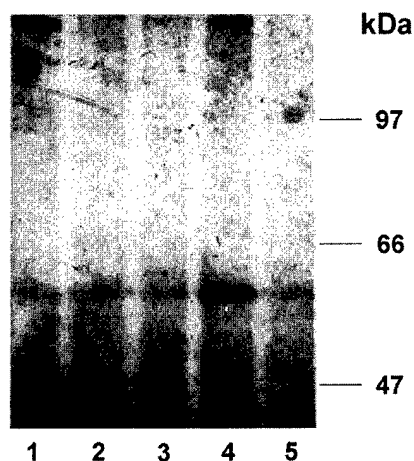


Fig. 3. Plasminogen-binding proteins isolated from the rat hepatocyte P-fraction by affinity chromatography. Lanes are labeled as sequential elution fractions, recovered after adding 15 mM EACA to the running buffer. Fraction 4 contains the major plasminogen-binding protein with a mass of 59 kDa.

graphy. EACA (15 mM) was used to elute bound proteins; elution fractions were analyzed by SDS-PAGE and silver-staining. A significant plasminogen-binding protein was not identified in these experiments.

Affinity chromatography was then performed to identify plasminogen-binding proteins in the detergent-insoluble portion of the P-fraction. Sodium deoxycholate (10 mM) was used to solubilize hepatocyte P-fraction. After centrifugation, the pellet was dissolved in 6 M urea and dialyzed back into 10 mM sodium deoxycholate without significant precipitation. The preparation was then subjected to plasminogen-affinity chromatography. Successive elution fractions, obtained after adding 15 mM EACA to the running buffer, are shown in Fig. 3. The 59 kDa protein bound to plasminogen-Sepharose and was the only major protein recovered in the EACA-eluent. These studies confirm and extend the results of the ligand blotting experiments by demonstrating that the 59 kDa protein binds plasminogen without exposure to SDS or immobilization on PVDF. Furthermore, the results of the chromatography experiments, performed with detergent-soluble and -insoluble fractions, indicate that the 59 kDa protein is the major plasminogen-binding protein in hepatocyte plasma membranes.

Identification of the 59 kDa protein

To identify the 59 kDa protein, sodium deoxycholate-insoluble material was isolated from the P-fraction. The 59 kDa protein was further purified by SDS-PAGE, transferred to PVDF and eluted for amino-terminal sequence analysis. Since the N terminus was apparently blocked, CNBr fragmentation was performed while the protein was adherent to the PVDF. The products were then eluted and subjected to SDS-PAGE and electroblotting. A major band at 12 kDa was isolated and subjected to amino-terminal sequence analysis, yielding a major and a secondary sequence. The major sequence, including the inferred N-terminal methionine residue, was MSTSGPRAFS. Amino acid yield ranged from 1.2 to 2.0 pmol, with the exception of the Ser residues that were recovered at lower yield, as expected. A search for homolo-

gous sequences was conducted in GenBank, using the Fasta program (Pearson, 1994). The major sequence was identical with that of mouse CK 8 (residues 12-21). Other significant homologies were detected exclusively with CK 8 from other species, including human (9/10) and potoroo (7/10).

The secondary sequence was present at approximately 25% of the molar yield of the major sequence and consisted of MDxIIAEVRA (a secondary amino acid was not clearly resolved at position three). The secondary sequence was 100% identical with amino acids 263-272 of mouse CK 8 and 89% identical with the comparable region of human CK 8. Significant homologies with proteins other than CK were not identified.

The identification of the plasminogen-binding protein as CK 8, or a CK 8-like protein, is consistent with the mass of the protein determined by SDS-PAGE and with the unique solubility properties of the protein, as determined by incubation with various detergents (Steinert and Roop, 1988). In hepatocytes and in other epithelial cells, CK 8 is typically recovered with CK 18 (Franke et al., 1981a,b), a slightly smaller protein that was observed in the detergent-insoluble fraction in Fig. 2. It is known that some CK 8 will partition into the plasma membrane fraction during subcellular fractionation (Hubbard and Ma, 1983). Furthermore, CK 8 is unique amongst the cytokeratins in that it has a C-terminal lysine that is conserved across species lines (Morita et al., 1988; Leube et al., 1986). As mentioned above, C-terminal lysine residues form a key element of most plasminogen-binding domains. To confirm the results of the microsequencing experiments, the detergent-insoluble portion of the hepatocyte P-fraction was subjected to western blot analysis with PCK-26, as previously described. The 59 kDa band bound antibody; no other immunopositive bands were detected (results not shown).

Immunofluorescence microscopy

The ability of CK 8 or a CK 8-like protein to bind plasminogen is significant, since CK 8 may be released by epithelial cells into the pericellular spaces and into the blood where plasminogen is present (Chan et al., 1986). CK 8 release from cells may be significantly increased in cancer (Bjorklund and Bjorklund, 1983). It has also been suggested that CK 8 is present on the external surfaces of breast carcinoma cells (Godfroid et al., 1991; Donald et al., 1990). If these reports are correct, then cell-surface CK 8 may function as a cellular plasminogen receptor; however, the presence of CK 8 on cell surfaces has been disputed (Riopel et al., 1993). Therefore, we undertook studies to determine whether hepatocytes and other epithelial cells express cell surface CK 8. The techniques used included immunofluorescence microscopy and immunoelectron microscopy. The advantage of these techniques is the ability to determine whether an antigen is distributed homogeneously across an entire population of cells or exclusively by a small subpopulation of cells.

To stain only cell-surface CK 8, CK 8-specific antibodies and secondary antibody were incubated with viable cells at 4°C in physiological buffers that contained BSA. Since all of the incubations were conducted with adherent cells on coverslips, the chance of cellular injury due to culture manipulation was minimized. Cells were not fixed until after all antibody incubations were completed.

Immunofluorescence microscopy studies of hepatocytes

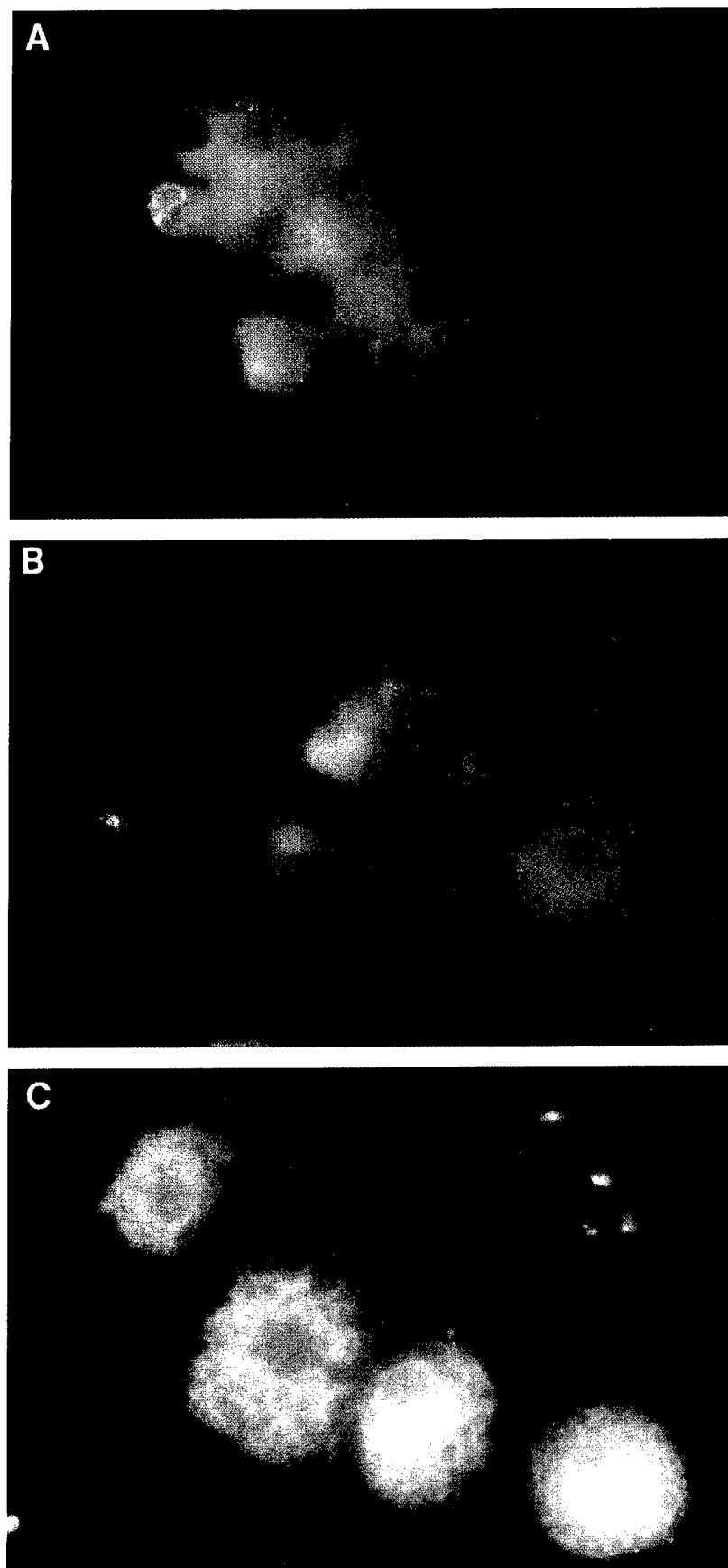


Fig. 4. Detection of CK 8 in viable, unpermeabilized hepatocytes by immunofluorescence microscopy. Primary rat hepatocytes were incubated with AB 6.01, followed by secondary antibody (FITC-anti-mouse IgG). To differentiate antibody binding from hepatocyte autofluorescence, the cells were imaged using a dual wavelength cube, exciting at both FITC and Texas Red wavelengths. Under these conditions, cytoplasmic autofluorescence appears red-white. (A) AB 6.01 labeling of a hepatocyte-cluster. (B) Individual hepatocytes are more prevalent. (C) Incubation with primary antibody was omitted; only cytoplasmic autofluorescence is seen.

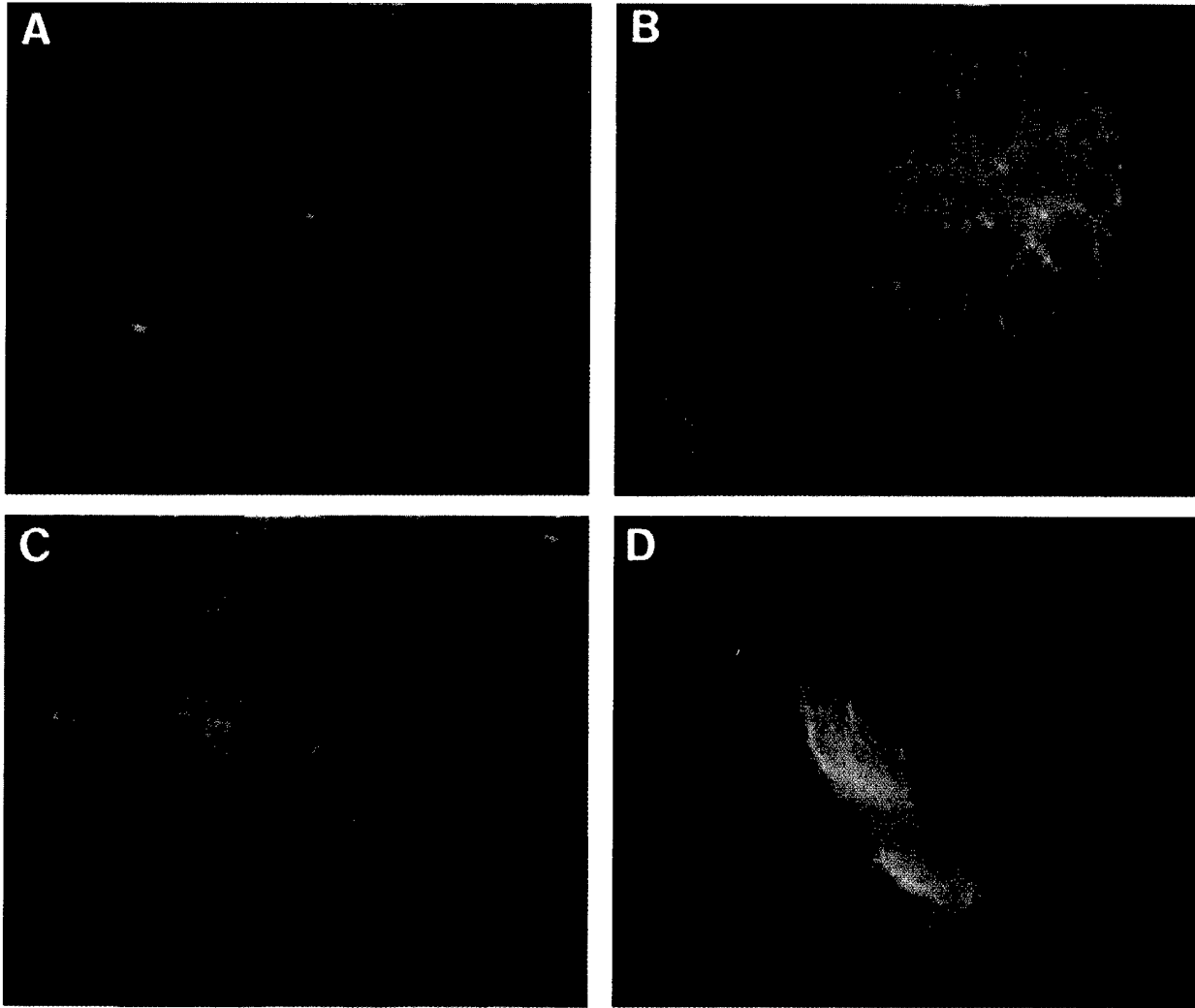


Fig. 5. Detection of CK 8 in viable, unpermeabilized HepG2 human hepatocellular carcinoma cells by immunofluorescence microscopy. (A-C) The cells were incubated with AB 6.01 and secondary antibody prior to fixation. (D) A typical HepG2 cell labeled with AB 6.01 after fixation and permeabilization with 0.02% saponin. The basket-like, perinuclear pattern of intracytoplasmic CK staining in D is readily distinguished from the pattern of cell-surface staining in A-C.

were first performed using AB 6.01 (Fig. 4). A punctate staining pattern was distributed uniformly over the entire surface of every cell. The extent of staining and the pattern were not affected by whether the cells were clustered in aggregates, as in panel A, or isolated, as in panel B. When the primary antibody was omitted, or when nonimmune mouse IgG was substituted for AB 6.01, only the inherent autofluorescence of the hepatocytes was detected (panel C). Similar punctate staining was observed using antibody PCK-26 (results not shown), which is specific for CK 8 in hepatocytes, since these cells do not express CK 5 or CK 6 (Moll et al., 1982; Franke et al., 1981a,b).

Since hepatocytes might be slightly damaged during isolation for primary culture, the immunofluorescence microscopy studies were extended by studying cell lines. Cultures of HepG2 cells were studied 48 hours after transfer to coverslips using AB 6.01. The labeling was similar to that observed with hepatocytes, except for the slightly finer punctate pattern in the HepG2 cells (Fig. 5). In panels A and

B, the plane of focus is low near the coverslip. Therefore, the immunofluorescence is seen in association with the edges of the cells, and at cell-cell contacts. In panel C, the plane of focus is near the apical surfaces of some cells, so that the punctate pattern of plasma membrane staining is more apparent. No immunofluorescence was observed when primary antibody was omitted. For comparison, some HepG2 cells were permeabilized with 0.02% saponin prior to incubation with primary antibody. The typical basket-like pattern of intracellular cytokeratin staining (panel D) was significantly different from that observed with viable, unpermeabilized cells.

Many of the previous conflicting studies regarding cell-surface CK 8 were performed with cultures of breast carcinoma cells (Godfroid et al., 1991; Donald et al., 1990). Therefore, we examined surface exposure of CK 8 in BT20 and MCF-7 breast carcinoma cells. Fig. 6 presents a composite of experiments performed with BT20 cells. AB 6.01 was used in panels A and C; M20 was used in panel B. The pattern of staining was comparable to that observed with the HepG2 cells and

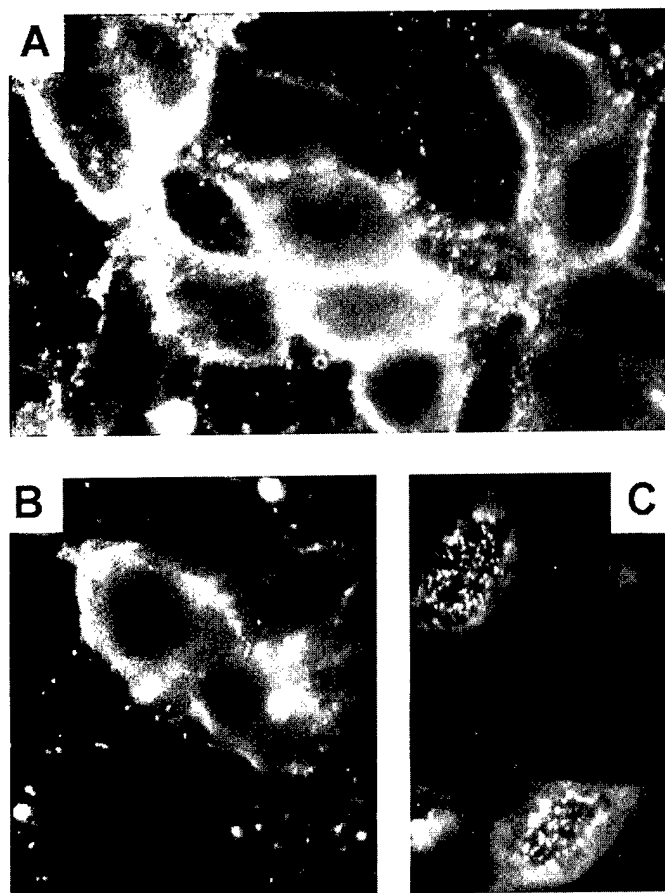


Fig. 6. Detection of CK 8 in viable, unpermeabilized BT20 human breast carcinoma cells by immunofluorescence microscopy. BT20 cells were incubated with AB 6.01 in A and C, or with M20 in B, followed by FITC-conjugated secondary antibody. All cells show diffuse punctate cell surface staining. In A and B, the plane of focus is near the coverslip to demonstrate peripheral, plasma-membrane-associated immunofluorescence. In C, the plane of focus is near the apical surface of the cell and shows the fine punctate pattern of immunofluorescence.

hepatocytes. The plane of focus in panels A and B is low, near the coverslip, demonstrating the plasma membrane distribution of immunofluorescence. Panel C shows punctate staining of apical cell surfaces. Equivalent results were obtained with MCF-7 cells (results not shown). Staining was not observed when primary antibody was omitted or when primary antibody was replaced with nonimmune mouse IgG. Furthermore, the pattern and intensity of staining remained unchanged when the cells were fixed prior to addition of secondary antibody (results not shown).

As a further control for the immunofluorescence microscopy experiments, MCF-7 and BT20 cells were examined using monoclonal antibody directed against the intracellular antigen, p120-GAP. Intense perinuclear fluorescence was observed in cells permeabilized with 0.02% saponin. By contrast, unpermeabilized cells demonstrated no immunofluorescence (results not shown).

Immunoelectron microscopy

To confirm that CK 8 or a CK 8-like antigen is associated with

the external surfaces of cells, immunoelectron microscopy experiments were performed. Primary antibody and colloidal gold adducts were incubated with viable cells at 4°C. Under these conditions, cell-associated gold should, hypothetically, indicate the presence of cell surface-bound primary antibody. Fig. 7 presents a composite of imaging studies with hepatocytes, HepG2 cells, BT20 and MCF-7 breast carcinoma cells. In A and B, hepatocytes were incubated with PCK-26. Colloidal gold was observed on the cell surfaces, primarily in association with microvilli and adjacent plasma membranes. No colloidal gold was observed in association with the intracellular spaces of the hepatocytes, suggesting that the cellular membranes were intact and that neither the primary antibody nor colloidal gold had access to the large intracellular pools of CK 8. When hepatocytes were incubated with colloidal gold adduct without prior incubation with PCK-26, essentially no colloidal gold was observed in association with the cell surfaces (results not shown).

The HepG2 cells and breast carcinoma cells were studied using AB 6.01. With each of these epithelial cells, the pattern of immunogold labeling was similar. Colloidal gold was localized exclusively to the cell surface and frequently observed in association with microvilli. As shown in C, large amounts of colloidal gold were observed in association with cellular projections near HepG2 cell-cell junctions. Omission of primary antibody consistently eliminated binding of colloidal gold-adduct to the cell surfaces. Clustering of colloidal gold particles, such as that observed in F, should be interpreted with caution, since the cells were exposed to Protein A-colloidal gold prior to fixation. The colloidal gold-adduct may promote clustering of antigen if the antigen is mobile in the plasma membrane.

In order to demonstrate that large amounts of antigen could be detected by immunoelectron microscopy if the cells were permeabilized, MCF-7 cells were incubated with AB 6.01 and Protein A-colloidal gold, post-embedding (H). The colloidal gold is observed in association with the cells, primarily overlying cytoplasm, as expected.

DISCUSSION

The role of plasmin in tumor invasion and other processes that require cellular migration has been studied extensively (Ellis and Dano, 1992; Vassalli et al., 1991). In this and related systems, association of plasminogen with the cell surface is probably critical. While recent studies have made significant advances in identifying important plasminogen receptors on various cells, epithelial cells have received little attention. These cells are important, since a large variety of common malignancies are of the epithelial cell-derived carcinoma family.

In this investigation, the primary plasminogen-binding protein in the plasma membrane fraction of hepatocytes was identified. This protein was CK 8 or a very closely related homologue of CK 8, as suggested by the molecular mass of the protein, the insolubility of the protein in various detergents, the primary sequence in two different regions of the structure, and the reactivity of the protein with an antibody that should be specific for CK 8 in western blots of hepatocyte extracts. The affinity of CK 8 for plasminogen is predicted by the presence

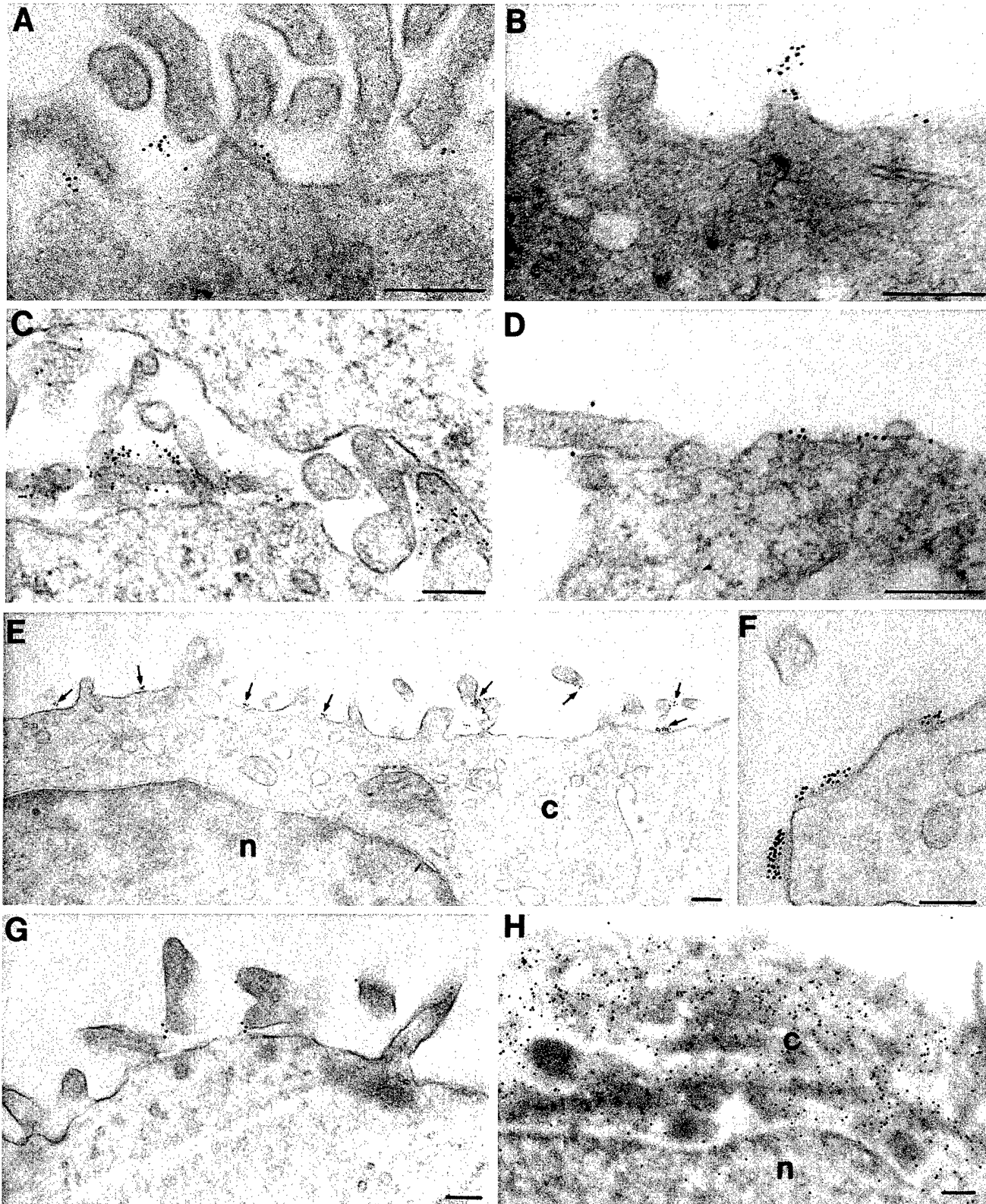


Fig. 7. Immunoelectron microscopy analysis of CK 8 in viable, unpermeabilized rat hepatocytes, HepG2, BT20 and MCF-7 cells. Rat hepatocytes, shown in A and B, were incubated with PCK-26, followed by anti-mouse IgG-colloidal gold adduct. HepG2 cells are shown in C and D, BT20 cells in E and F, and MCF-7 cells are shown in G. The cells in these panels were incubated with AB 6.01, followed by Protein A-colloidal gold adduct. The arrows in E indicate clusters of colloidal gold. In H, MCF-7 cells were incubated with AB 6.01 and Protein A-colloidal gold adduct post-embedding. This procedure exposes intracytoplasmic CK to antibody. c, cytoplasm; n, nucleus. Bars, 200 nm.

of a conserved C-terminal lysine in the CK 8 sequence. Although this is the first description of this novel activity for CK 8, the significance of our observation is dependent on the extent to which plasminogen has access to CK 8.

CK 8 is one of at least 21 related cytokeratins that form intermediate filaments in various epithelial cells and carcinoma cells; however, many cell types express only one acidic (type I) CK and one neutral-basic (type II) CK (Moll et al., 1982). An example is the hepatocyte, which expresses CK 8 and CK 18 (Franke et al., 1981a,b). CK 8-containing intermediate filaments associate extensively with the internal leaflet of the plasma membrane. CK 8 or CK 8 fragments have also been detected in conditioned culture medium (Chan et al., 1986) and in the serum and body fluids of patients with a variety of cancers (Bjorklund and Bjorklund, 1983). It is not clear whether the released CK *in vivo* is derived primarily from viable or dying cells. Nevertheless, this pool of CK 8 is present in physiological spaces that contain plasminogen. Therefore, it is feasible that CK 8 functions as a plasminogen-binding protein *in vivo*.

Previous studies have provided evidence for the presence of CK 8 on the external surfaces of cultured breast cancer cell lines (Godfroid et al., 1991; Donald et al., 1991). This association may be accomplished in several ways. It is feasible that CK 8 projects through the plasma membrane as part of a protein complex so the CK 8 does not require a transmembrane domain. CK 8 may associate with the plasma membrane after secretion by cells (Riopel et al., 1993). It has also been demonstrated that CK 8 covalently binds to plasma membrane lipids (Asch et al., 1993); these covalent conjugates may conceivably translocate to the outer membrane leaflet during normal membrane shedding. Our further investigation of this issue was prompted by the work of Riopel et al. (1993), which suggested that detection of cell-surface CK is artifactual. These investigators presented a convincing argument regarding the inadequacy of methods such as cell surface radioiodination for the demonstration of cell surface CK 8. Using such methods, even a rare injured or permeabilized cell might confound the data, since the amount of intracellular CK 8 greatly exceeds that which might be present on the cell surface.

The immunofluorescence microscopy studies presented here are the first of their kind with hepatocytes, HepG2 hepatocellular carcinoma cells and BT-20 breast carcinoma cells. MCF-7 cell immunofluorescence microscopy studies using antibody 6.01 were reported previously by Donald et al. (1991). We chose immunofluorescence microscopy for antibody detection instead of other techniques, such as FACS analysis, so that adherent cultures might be studied without using potentially damaging techniques to release cells. Our results suggest a similar pattern of punctate cell surface CK 8-antigen detection with each of the cell types examined. The protocols used in the immunofluorescence microscopy studies were designed so as to minimize the possibility of cellular injury or death. The uniform pattern of immunofluorescence through the entire population of cells in each preparation demonstrates that the antibody-accessible CK 8 is not contributed by a small subpopulation of damaged cells. Furthermore, the punctate pattern of fluorescence in the intact cells is readily distinguishable from that observed with permeabilized cells. Overall, three separate antibodies were used in the immunofluorescence studies with equivalent results: PCK-26 with hepatocytes; AB

6.01 with hepatocytes, HepG2 cells and breast carcinoma cells; and M20 with breast carcinoma cells. The use of multiple antibodies with well-characterized specificities minimizes the chance that we are detecting a cell-surface protein that is completely unrelated to CK 8. Furthermore, our western blot analyses of whole cell extracts from each of the studied cell types confirmed the expected specificities for each antibody (PCK-26, M20, AB 6.01) (results not shown). Therefore, the immunofluorescence studies strongly suggest the presence of CK 8 or a CK 8-like protein on the surfaces of viable epithelial cells.

Immunoelectron microscopy experiments were performed to confirm that our methods detect cell-surface antigen and not intracytoplasmic antigen. As with the immunofluorescence studies, electron microscopy revealed a similar pattern of antigen expression in all of the epithelial cells studied. Although colloidal gold was distributed across the entire cell surface, we always observed gold preferentially associated with microvilli and the plasma membranes adjacent to microvilli. The pattern of antigen detection by immunogold reported here in hepatocytes, HepG2, and breast carcinoma cells is similar to that reported by Donald et al. (1991) in squamous cell carcinoma.

Our finding that a cytoskeletal protein is located on the cell surface where it may function as an important receptor is not unique. α -Actin has been reported to be present on the surfaces of multiple cell types, including fibroblasts, smooth muscle cells and endothelium (Chen et al., 1978; Jones et al., 1979; Moroianu et al., 1993). Endothelial cell-surface α -actin may function as a receptor for angiogenin and thereby regulate angiogenesis (Moroianu et al., 1993).

The studies presented in this investigation do not permit a determination of the extent to which extracellular CK 8 contributes to the total specific plasminogen-binding capacity of the various cell types. The CK 8-specific antibodies used in this study were of the IgG₁ subtype and therefore all have carboxyl-terminal lysine residues. Although we have performed experiments demonstrating that M20 and PCK-26 substantially inhibit plasminogen binding to each of the cells under investigation (AB 6.01 was a weaker inhibitor, results not shown), Ellis and Dano (1993) demonstrated that IgG₁ antibodies bind plasminogen. Therefore, our results may be explained by antibody binding to plasminogen receptors on the cell surface or by plasminogen-antibody complex formation in solution. To resolve this problem, we are currently attempting to raise monoclonal antibodies specific for the C terminus of CK 8. If an appropriate hybridoma can be obtained, competition binding studies will be performed with Fab fragments.

Numerous studies have shown high levels of CK 8 in malignant cells. In transitional cell carcinoma and squamous cell carcinoma, CK 8 and CK 18 have been detected at increased levels by immunohistochemistry at the tumor invasion front (Schaafsma et al., 1991, 1993). The most tumorigenic clones of SW 613-S cells express the highest levels of CK 8 mRNA (Modjtahedi et al., 1992). CK 8 is aberrantly induced in H-*ras* transformed epidermal cells (Diaz-Guerra et al., 1992). Furthermore, mouse L fibroblasts, which lack CK 8 and 18, show increased motility and penetration of Matrigel *in vitro* after transfection with CK 8 and CK 18 DNAs (Chu et al., 1993). Motility and Matrigel penetration are processes which are dependent on the cell-surface tumor invasion pro-

teinas cascade. Whether cells that express increased levels of CK 8 show an incremental increase in cell surface CK 8 which, by binding plasminogen, supports or accelerates cellular migration and invasion is currently under investigation.

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Cytokeratin 8 released by breast carcinoma cells *in vitro* binds plasminogen and tissue-type plasminogen activator and promotes plasminogen activation

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Cell-surface activation of plasminogen may be important in diseases that involve cellular migration, including atherosclerosis and tumour invasion/metastasis. Cytokeratin 8 (CK 8) has been identified as a plasminogen-binding protein expressed on the external surfaces of hepatocytes and breast carcinoma cells [Hembrough, Vasudevan, Allietta, Glass and Gonias (1995) *J. Cell Sci.* 108, 1071–1082]. In this investigation, we demonstrate that a soluble form of CK 8 is released into the culture medium of breast cancer cell lines. The released CK 8 is in the form of variably sized polymers that bind plasminogen and promote the activation of [Glu¹]plasminogen and [Lys⁷⁸]plasminogen by single-chain tissue-type plasminogen activator (sct-PA). To assess

the mechanism by which CK 8 promotes plasminogen activation, CK 8 was purified from rat hepatocytes and immobilized in microtitre plates. Immobilized CK 8 bound ¹²⁵I-plasminogen and ¹²⁵I-sct-PA in a specific and saturable manner. The *K_D*s were 160 ± 40 nM and 250 ± 48 nM, respectively. Activation of plasminogen bound to immobilized CK 8 was accelerated compared with plasminogen in solution, as determined using a coupled-substrate fluorescence assay and SDS/PAGE. The ability of CK 8 to promote plasminogen activation may be important in the pericellular spaces surrounding breast cancer cells and at the cell surface.

INTRODUCTION

Tissue-type plasminogen activator (t-PA) is one of the two major plasminogen activators *in vivo*; however, in the absence of protein cofactors, the efficiency of plasminogen activation by t-PA is poor. Proteins that bind t-PA and/or plasminogen have been identified in the plasma and basement membranes [1,2]. The most important of these, from the standpoint of haemostasis, is fibrin, which substantially increases the catalytic efficiency of plasminogen activation [3].

Many cells in culture express specific and saturable binding sites for t-PA and plasminogen. The affinity of cellular receptors for plasminogen is typically low; however, the total cellular plasminogen binding capacity is high (10⁵–10⁷ sites per cell) [4]. Binding of plasminogen to certain cells, including endothelial cells [5] and hepatocytes [6], promotes activation by t-PA. Like other plasminogen-binding interactions, those involving cellular receptors utilize the five tandem plasminogen kringle domains, three of which (K1, K4 and K5) demonstrate affinity for lysine residues in other proteins [1,2]. The kringle-1 domain contains the highest-affinity lysine-binding site and interacts preferentially with C-terminal lysines [7–10]. Thus, plasma membrane proteins with extracellular C-terminal lysines are most likely to function as plasminogen receptors.

Several cellular proteins have been identified as candidate plasminogen receptors, including α -enolase, on monocytoic cells, and annexin II, on endothelial cells [10,11]. Although these proteins are primarily intracellular in location, each has been identified on the external cell surface, using immunofluorescent

antibody-based techniques [10,11]. The structure of α -enolase includes a C-terminal lysine [10]; annexin II does not have a C-terminal lysine and is thus dependent on modification by plasmin or another lysine-specific proteinase in order to acquire plasminogen-binding activity [11].

Recently, we identified cytokeratin 8 (CK 8) as a candidate epithelial cell plasminogen receptor [12]. CK 8 is an intermediate filament protein [13]; however, using fluorescence and immunoelectron microscopy, we demonstrated CK 8 or a CK 8-like protein on the external surfaces of hepatocytes, breast carcinoma cells and hepatocellular carcinoma cells. CK 8 contains a C-terminal lysine residue [14]. Thus, CK 8 has intrinsic plasminogen binding capacity and does not require prior proteolytic modification in order to bind plasminogen.

The interaction of plasminogen with CK 8 may not be restricted to the cell surface since cytokeratins are released in significant quantities by cancer cells *in vitro* and by carcinomas *in vivo*. CK 8 has been identified as a major component of Tissue Polypeptide Antigen, a tumour-associated marker, found in the serum and body fluids of cancer patients [15,16]. Levels of Tissue Polypeptide Antigen have been used to monitor the progression of malignancies [17]. CK 8 is also released into the culture medium of breast cancer cells *in vitro* [18,19]. Whether the released forms of CK 8 retain the ability to bind plasminogen is unknown.

In this investigation, we confirm the results of previous studies [18] by demonstrating the presence of CK 8 in conditioned medium of breast cancer cells *in vitro*. We then demonstrate, for the first time, that the soluble form of CK 8, recovered in cancer

Abbreviations used: t-PA, tissue-type plasminogen activator; sct-PA, single-chain tissue plasminogen activator; CK 8, cytokeratin 8; [Glu¹]plasminogen, native plasminogen; [Lys⁷⁸]plasminogen, proteolytically modified plasminogen with Lys⁷⁸ as its N-terminus; EBSS, Earle's balanced salt solution; EHB, EBSS, 10 mM Hepes, 10 mg/ml BSA; S-2251, D-valyl-L-leucyl-L-lysine-*p*-nitroanilide; S-2288, D-isoleucyl-L-prolyl-L-arginine-*p*-nitroanilide; VLK-AMC, D-valyl-L-leucyl-L-lysine-5-aminomethylcoumarin; PPACK, phenylprolylarginylchloromethane; BCA, bicinchoninic acid; E-64, L-trans-epoxysuccinyl-leucylamido(4-guanido)butane; ϵ ACA, ϵ -aminohexanoic acid; u-PA, urokinase; tcn-PA, two-chain urokinase; DTT, dithiothreitol.

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cell-conditioned medium, retains plasminogen-binding activity. Purified CK 8 also binds t-PA and enhances the efficiency of plasminogen activation by t-PA. Thus, soluble CK 8, released from cancer cells *in vivo*, may promote plasminogen activation in malignancy.

MATERIALS AND METHODS

Materials

D-Valyl-L-leucyl-L-lysine-*p*-nitroanilide (S-2251) and D-isoleucyl-L-prolyl-L-arginine-*p*-nitroanilide (S-2288) were from Kabi Vitrum (Stockholm, Sweden). D-Valyl-L-leucyl-L-lysine-5-aminomethylcoumarin (VLK-AMC) was from Enzyme Systems Products (Livermore, CA, U.S.A.). Phenylprolylarginylchloromethane (PPACK) was from Calbiochem (San Diego, CA, U.S.A.). Leupeptin and L-*trans*-epoxysuccinyl-leucylamido(4-guanido)butane (E-64) were from Boehringer Mannheim. Aprotinin, chloramine T, ϵ -aminohexanoic acid (ϵ ACA), PMSF, BSA and bichoninic acid solution (BCA) were from Sigma Chemicals (St. Louis, MO, U.S.A.). Na¹²⁵I was from Amersham International (Arlington Heights, IL, U.S.A.). Iodobeads were purchased from Pierce (Rockford, IL, U.S.A.). Earle's balanced salt solution (EBSS) was from Gibco Laboratories (St. Lawrence, MA, U.S.A.). Cell culture plasticware was from Costar (Cambridge, MA, U.S.A.).

Proteins and antibodies

[Glu¹]Plasminogen (native plasminogen) was purified from human plasma by the method of Deutsch and Mertz [20]. [Glu¹]Plasminogen was converted into [Lys⁷⁸]plasminogen (proteolytically modified plasminogen with Lys⁷⁸ as its N-terminus) by incubation with plasmin-Sepharose. Single-chain t-PA (sct-PA) was from American Diagnostica. The concentration of active sct-PA was determined by the velocity of S-2288 hydrolysis, using the kinetic constants ($K_m \sim 1.0$ mM, $k_{cat} \sim 26$ s⁻¹) provided by the manufacturer. Recombinant single-chain urokinase (u-PA) was generously provided by Dr. Jack Henkin (Abbott Laboratories) and converted into two-chain urokinase (tcu-PA) by incubation with plasmin-Sepharose. Monoclonal antibody PCK-26, which recognizes CK 5, CK 6 and CK 8, was from Sigma. Of these three cytokeratins, only CK 8 is expressed by breast carcinoma cells [13].

Preparation of BT20 cell-conditioned medium

BT20 breast carcinoma cells were allowed to reach 60–75% confluency and then cultured in serum-free medium (RPMI 1640 with 100 units/ml penicillin and 100 μ g/ml streptomycin) for 4 days. The conditioned medium was collected and centrifuged at 1000 *g* for 10 min to pellet cellular debris and then concentrated 10-fold using an Amicon concentrator with a YM-10 membrane.

Concentrated BT20 cell-conditioned medium (0.5 ml) was subjected to molecular exclusion chromatography on a Superose 12 column, using a flow rate of 0.4 ml/min. Elution of proteins was detected by constant monitoring of absorbance at 280 nm. Fractions were collected at 1 min intervals. CK 8 was detected in chromatography fractions by immunoblot analysis using antibody PCK-26. In order to calibrate the column, the following proteins were subjected to chromatography under identical conditions: α_2 -macroglobulin (720 kDa), mouse IgG (150 kDa), BSA (66 kDa) and cytochrome *c* (14 kDa).

Effects of BT20 cell-conditioned medium on plasminogen activation by t-PA

Activation of [Glu¹]plasminogen and [Lys⁷⁸]plasminogen (0.05–1.0 μ M) by sct-PA (2 nM), in the presence and absence of BT20 cell-conditioned medium, was studied using a continuous assay and the plasmin-specific substrate, S-2251 (0.5 mM). The BT20 cell-conditioned medium was preincubated with plasminogen in the sample cuvette of a Hewlett-Packard 8450 diode-array spectrophotometer for 30 min at 22 °C. sct-PA and S-2251 were added to start the reaction. In the final incubation mixture, the BT20 cell-conditioned medium was diluted 1:2. Absorbance at 406 nm was measured at 5 s intervals for 300 s. To determine rates of plasminogen activation, absorbance measurements were transformed using the first derivative function (dA_{406}/dt). Kinetic constants for the hydrolysis of S-2251 by plasmin ($K_m = 180$ μ M, $k_{cat} = 12$ s⁻¹) were used to convert data into plots of active plasmin concentration against time. In control experiments, we analysed S-2251 hydrolysis in the presence of BT20 cell-conditioned medium and plasminogen (no sct-PA) or in the presence of BT20 cell-conditioned medium and sct-PA (no plasminogen). In both cases, significant substrate hydrolysis was not observed within 600 s. Finally, unconditioned cell culture medium, at the dilution used in our experiments, did not significantly affect the kinetics of activation of [Glu¹]plasminogen or [Lys⁷⁸]plasminogen by sct-PA.

CK 8 purification

CK 8 was purified by the method of Achtstaetter et al. [21]. Rat hepatocytes were collected as previously described [12] and homogenized in EBSS with 10 mM Hepes, 0.1 mM dithiothreitol (DTT), 1.0 mM PMSF, 2.0 μ M E-64, 10 mM EDTA and 10 μ M aprotinin. The homogenate was centrifuged at 1250 *g* for 15 min. The resulting pellet was extracted with 1.0% Triton X-100 for 1 h at 4 °C and then subjected to centrifugation at 2500 *g* for 5 min. The pellet was resuspended in 1.5 M KCl, 0.5% Triton X-100, 10 mM Hepes, 5 mM EDTA, 5 mM DTT at 4 °C and forced through a syringe to shear DNA. Centrifugation was performed again. The pellet was rinsed with 20 mM sodium phosphate, 150 mM NaCl, pH 7.4, and solubilized in 9.5 M urea, 10 mM Tris/HCl, 5 mM DTT, pH 8.8, for 2 h. This solution, which includes CK 8, CK 18 and some contaminating proteins, was clarified by centrifugation at 14000 *g* for 20 min and dialysed against 8 M urea, 30 mM Tris/HCl, 5 mM DTT, pH 8.8. The preparation was then subjected to DEAE-Sepharcel ion-exchange chromatography. The column was equilibrated in 8 M urea, 30 mM Tris/HCl, pH 8.0, and eluted with a linear gradient of 0 to 100 mM guanidine hydrochloride. Samples were screened by absorbance at 280 nm and by SDS/PAGE/Western blot analysis using antibody PCK-26. Fractions containing purified CK 8 were pooled and stored at room temperature.

Ligand blotting

BT20 cell-conditioned medium or purified CK 8 was subjected to SDS/PAGE [22] and electrotransferred to poly(vinylidene difluoride) (PVDF) membranes (Millipore) using a Hoefer Transphor apparatus (2 h, 0.5 A). In some studies, the transferred proteins were stained with 0.2% (w/v) Coomassie Blue R250 (Bio-Rad, CA, U.S.A.). Otherwise, the membranes were blocked with 5% non-fat dried milk, rinsed twice with 20 mM sodium phosphate, 150 mM NaCl, 0.1% (v/v) Tween-20, pH 7.4 (PBS-T), and then incubated with ¹²⁵I-plasminogen (10 nM) and aprotinin (10 μ M), in the presence and absence of 10 mM ϵ ACA or a 50-fold molar

excess of non-radiolabelled plasminogen. To determine radioligand binding, the blots were rinsed three times for 15 min in PBS-T, dried and autoradiographed, or analysed with a Phosphorimager.

Binding of plasminogen and t-PA to immobilized CK 8

Purified CK 8 (100 µg/ml) in 8 M urea was diluted 1:3 with 20 mM sodium phosphate, 150 mM NaCl, pH 7.4, in 48-well cell culture plates and incubated for 1.5 h at 37 °C. The plates were rinsed three times and then blocked by the addition of BSA (10 mg/ml) in EBSS, 10 mM Hepes, pH 7.4, (EHB) for 1.5 h at 37 °C. Control plates were blocked with BSA without prior adsorption of CK 8. All plates were stored at 4 °C until use. The amount of CK 8 immobilized per well was 0.43 ± 0.07 µg ($n = 6$), as determined by BCA assay of SDS-extracted samples.

Plasminogen and sct-PA were radioiodinated using Iodobeads (Pierce). The specific activities of both proteins ranged from 1–2 µCi/µg. Increasing concentrations of either 125 I-plasminogen or 125 I-sct-PA were incubated in CK 8-coated and control wells for 1 h at 22 °C. Plates were then washed three times with EHB. Bound radioligand was recovered by incubation with 1% SDS, 0.1 M NaOH and quantified in a gamma counter. Non-specific 125 I-plasminogen binding was defined as residual binding in the presence of 10 mM εACA or a 50-fold molar excess of plasminogen (either method yielded equivalent results). For 125 I-sct-PA concentrations up to 0.25 µM, non-specific binding was determined using a 50-fold molar excess of non-radiolabelled t-PA. Non-specific binding of 125 I-sct-PA was plotted as a function of 125 I-sct-PA concentration and extrapolated to higher concentrations, assuming a continuously linear relationship, in order to conserve material.

Activation of plasminogen bound to immobilized CK 8 as determined by fluorescent substrate hydrolysis

Various concentrations of [Glu¹]plasminogen were incubated in CK 8-coated wells for 1 h at 22 °C. The plates were rinsed three times with EHB to remove unbound plasminogen. sct-PA (10 nM) and the fluorescent plasmin substrate, VLK-AMC (0.5 mM), were then added. Initial rates of substrate hydrolysis were detected by measuring fluorescence emission at 5 s intervals using a Cytofluor 2350 fluorescence plate reader (Millipore). The excitation wavelength was 380 nm and the emission wavelength was 480 nm (5 nm slit widths). Levels of CK 8-associated plasminogen, available for activation by sct-PA, were determined in separate 125 I-plasminogen binding studies. Equivalent amounts of plasminogen, in solution, were activated by 10 nM sct-PA in BSA-blocked wells (no CK 8).

In control experiments, hydrolysis of VLK-AMC (0.5 mM) by equal amounts of free (pre-activated) plasmin and CK 8-associated plasmin were compared. The velocity of VLK-AMC hydrolysis was $97 \pm 6\%$ higher for free plasmin ($n = 6$).

Activation of plasminogen bound to immobilized CK 8 as determined by SDS/PAGE

125 I-[Glu¹]plasminogen (1.0 µM) was incubated in wells with immobilized CK 8 for 1 h at 22 °C. Aprotinin (10 µM) was included in the incubation mixture. After washing the plates three times with EHB to remove unbound plasminogen, 10 nM sct-PA and 10 µM aprotinin were added. At various times, the sct-PA was inhibited by the addition of 10 µM PPACK. Laemmli SDS sample buffer with reductant (7 mg/ml DTT) was then added to the wells. Samples were subjected to SDS/PAGE and autoradiography. Plasminogen activation was detected by con-

version of the single-chain zymogen (90 kDa) into the two-chain active species.

When 1.0 µM 125 I-[Glu¹]plasminogen was incubated in the CK 8-coated wells, 2.0 ± 0.3 pmol ($n = 5$) associated with the immobilized phase. In control experiments, the equivalent amount of 125 I-plasminogen was added to BSA-blocked wells, without CK 8. sct-PA and aprotinin were then added and plasminogen activation was studied, as a function of time, by SDS/PAGE and autoradiography.

RESULTS

Identification of CK 8 in BT20 cell-conditioned medium

BT20 cell-conditioned medium was concentrated 10-fold and subjected to SDS/PAGE and Western blot analysis with antibody PCK-26. A prominent species with an apparent mass of 56 kDa was detected, together with a second less-intense band with an apparent mass of 53 kDa (Figure 1, lane B). The molecular mass of human CK 8 is about 55 kDa [13]. The Western blot analysis suggests that the BT20 cell-conditioned medium contains intact CK 8 (apparent mass of 56 kDa) and a partially degraded form of CK 8. Analysis of three separate preparations demonstrated the same two bands; the amount of the 53 kDa species was slightly increased in one of the three (results not shown).

Plasminogen-binding proteins in the BT20 cell-conditioned medium were identified by ligand blotting. A single protein, with identical electrophoretic mobility to intact CK 8, bound 125 I-plasminogen (Figure 1, lane C). No other plasminogen-binding proteins were detected. The 53 kDa band did not bind 125 I-plasminogen. This result suggests that the 53 kDa species may be CK 8, proteolytically modified at the C-terminus, so that the C-terminal Lys residue is deleted.

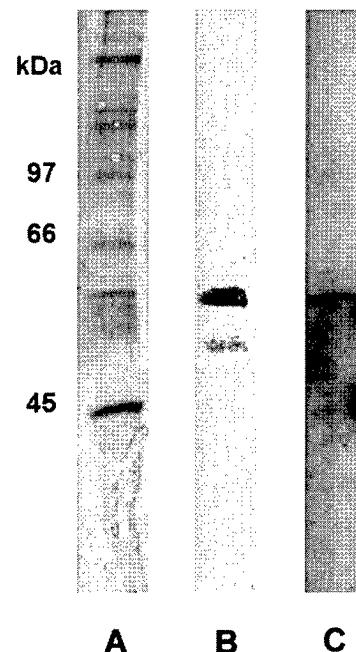


Figure 1 SDS/PAGE analysis of BT20 cell-conditioned medium

Concentrated BT20 cell-conditioned medium (100 µg of protein) was subjected to SDS/PAGE on 10% acrylamide slabs and transferred to poly(vinylidene difluoride) membranes. Resolved proteins were stained with Coomassie Blue (A); subjected to Western blot analysis with monoclonal antibody PCK-26 (B); or ligand blotted with 10 nM 125 I-plasminogen (C).

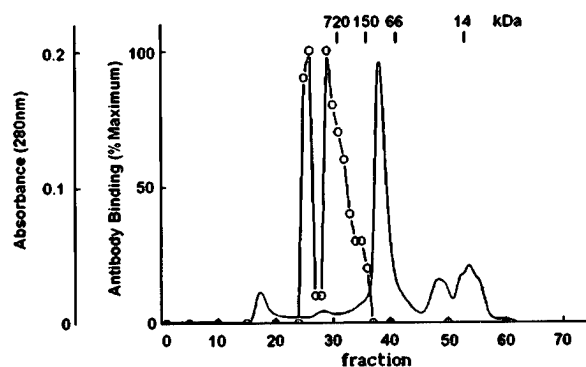


Figure 2 Superose 12 chromatography of BT20 cell-conditioned medium

BT20 cell-conditioned medium (500 μ g of protein) was subjected to molecular exclusion chromatography on a Superose 12 column. Protein elution was detected by continuous monitoring of absorbance at 280 nm (unbroken curve). CK 8 was detected by dot-blot analysis with antibody PCK-26 (○).

Characterization of CK 8 in BT20 cell-conditioned medium

BT20 cell-conditioned medium was subjected to molecular exclusion chromatography on a Superose 12 column. CK 8 was detected in elution fractions by dot-blot analysis with antibody PCK-26. Figure 2 shows that the CK 8 was recovered over a wide range of fractions which, by comparison with the chromatography standards, correspond in apparent molecular mass from 150 kDa to over 1000 kDa. These results suggest that the CK 8 in BT20 cell-conditioned culture medium is in the form of variably sized polymers or complexes. The chromatography standards were globular proteins; if the CK-8-containing complexes were highly asymmetric, then the apparent masses are overestimated by comparison with the standards.

Effect of soluble CK 8 on plasminogen activation by sct-PA

Some plasminogen-binding proteins enhance the rate of plasminogen activation by t-PA, especially when the proteins bind plasminogen activator as well [2]. Thus, we tested the ability of BT20 cell-conditioned medium to promote plasminogen activation by sct-PA. It was assumed that any changes in the

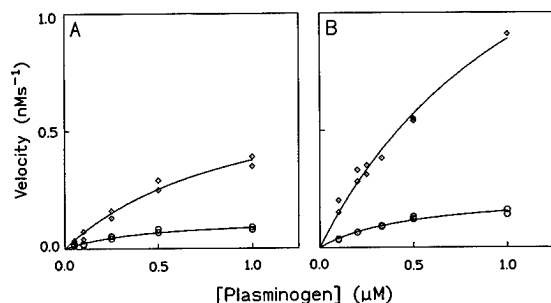


Figure 3 Effects of BT20 cell-conditioned medium on the activation of [Glu¹]plasminogen and [Lys⁷⁸]plasminogen by sct-PA

Increasing concentrations of [Glu¹]plasminogen (A) or [Lys⁷⁸]plasminogen (B) (0.05–1.0 μ M) were activated with 2 nM sct-PA in the presence (◇) and absence (○) of a 1:2 dilution of BT20 cell-conditioned medium. The initial velocity of plasminogen activation is plotted against plasminogen concentration.

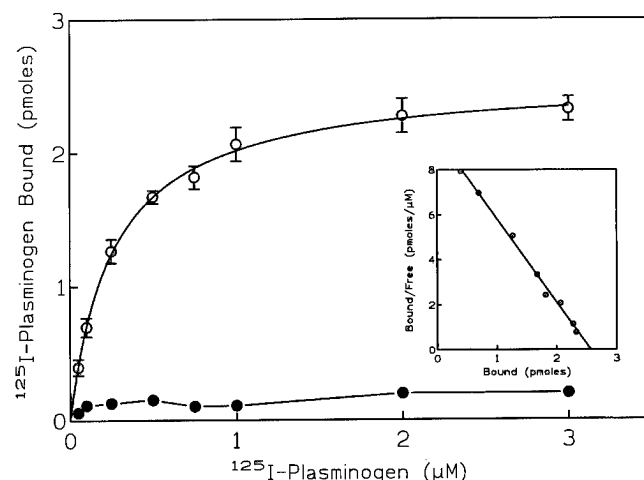


Figure 4 125 I-plasminogen binding to immobilized CK 8

A representative study showing specific binding of 125 I-plasminogen to immobilized CK 8 (○) and to BSA-blocked wells (●). Each point represents the average of four replicate determinations ($\pm$ S.E.M.) in one of four separate experiments. The Scatchard transformation of the data for plasminogen binding to CK 8 is shown in the inset.

kinetics of plasminogen activation would be due to CK 8, since CK 8 was the only plasminogen-binding protein in BT20 cell-conditioned medium. Figure 3 shows a representative experiment in which [Glu¹]plasminogen or [Lys⁷⁸]plasminogen was activated by sct-PA in the presence of S-2251. Initial rates of activation were determined and plotted against plasminogen concentration. In the absence of BT20 cell-conditioned medium, [Lys⁷⁸]plasminogen was activated more rapidly than [Glu¹]plasminogen, as expected. Removal of the 77-amino-acid N-terminal pre-activation peptide, in [Lys⁷⁸]plasminogen, causes the zymogen to adopt a more open, readily activated conformation [23,24]. In the presence of conditioned medium, both plasminogens were activated at increased rates. When the BT20 cell-conditioned medium was passed through a sterile Acrodisc 0.2 μ m filter (Gelman), the ability of the preparation to promote plasminogen activation was unchanged.

In separate experiments, the activation of [Glu¹]plasminogen (1.0 μ M) by 5 nM t-PA was assessed in the presence and absence of BT20 cell-conditioned medium. The [Glu¹]plasminogen was pre-incubated with the conditioned medium for 30 min, according to the standard protocol followed with sct-PA; however, the velocity of plasminogen activation by t-PA was not significantly affected by the conditioned medium (the rate of plasminogen activation was decreased by $3 \pm 10\%$ in the presence of the medium, $n = 4$).

The increased rate of activation of [Lys⁷⁸]plasminogen by sct-PA, in the presence of BT20 cell-conditioned medium, suggests that the mechanism is not limited to plasminogen conformational change. To better address the mechanism by which CK 8 stimulates plasminogen activation, CK 8 was purified from hepatocytes. The effects of purified CK 8 on plasminogen activation were then studied as a model of interactions that may occur with tumour cell-released CK 8.

Binding of plasminogen and sct-PA to immobilized CK 8

125 I-[Glu¹]plasminogen bound to immobilized CK 8 at 22 °C. Figure 4 shows that binding was specific and saturable. By

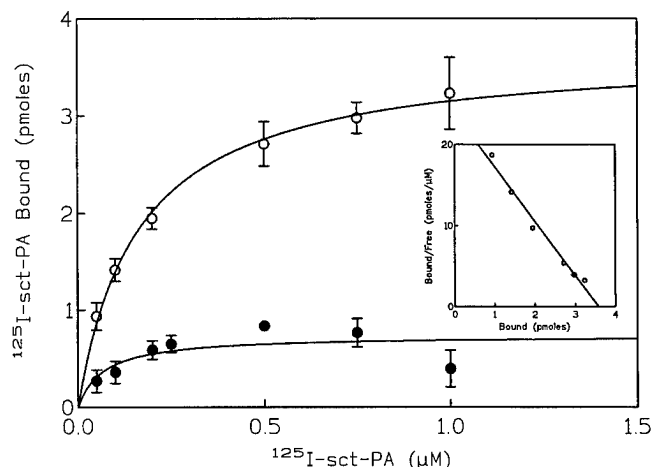


Figure 5 ^{125}I -sct-PA binding to immobilized CK 8

A representative study showing specific binding of ^{125}I -sct-PA to immobilized CK 8 (○) and BSA-blocked wells (●). Each point represents the average of four replicate determinations in one of three separate experiments. The Scatchard transformation of the data for sct-PA binding to CK 8 is shown in the inset.

Scatchard analysis, the K_D was 160 ± 40 nM and the $B_{\max}$ was 3.6 ± 0.7 pmol/well ($n = 4$). At saturation, 0.5 mol of plasminogen was bound per mol of immobilized CK 8 monomer. Non-specific plasminogen binding accounted for less than 15% of total binding through the entire plasminogen concentration range. Plasminogen binding to BSA-coated wells was negligible.

^{125}I -sct-PA also bound to immobilized CK 8 at 22 °C (Figure 5). Binding was specific and saturable with a K_D of 250 ± 48 nM, and a $B_{\max}$ of 4.0 ± 0.7 pmol/well ($n = 3$). Non-specific binding accounted for less than 10% of total binding for ^{125}I -sct-PA concentrations up to $0.25 \mu\text{M}$.

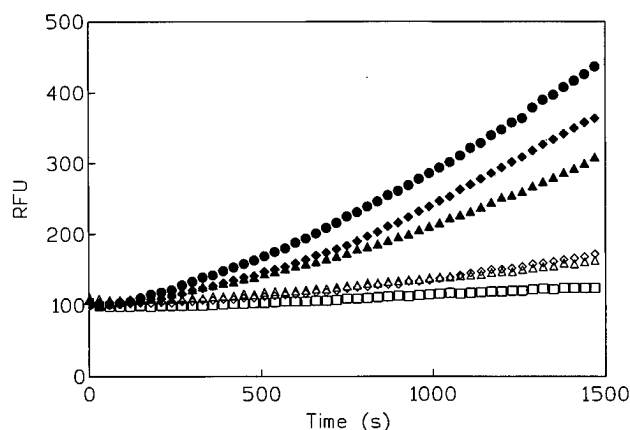


Figure 6 Activation of CK 8-associated plasminogen by sct-PA as determined by fluorescent substrate hydrolysis

CK 8-associated plasminogen [2.0 pmol (●), 1.3 pmol (◆), 1.0 pmol (▲)] was activated with 10 nM sct-PA in the presence of 0.5 mM VLK-AMC. The identical protocol was followed using plasminogen in solution [2.0 pmol (◇), 1.3 pmol (△), 1.0 pmol (□)], in BSA-coated wells. Fluorescent substrate hydrolysis was monitored continuously at 480 nm.

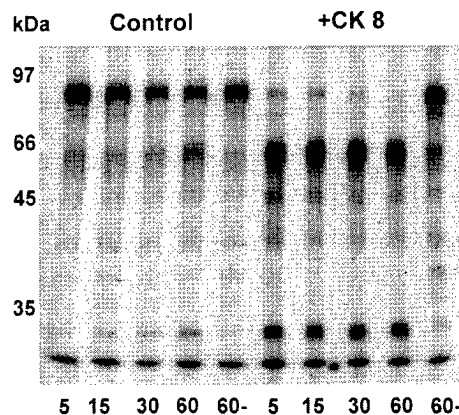


Figure 7 SDS/PAGE analysis of the activation of CK 8-associated ^{125}I -plasminogen by sct-PA

^{125}I -plasminogen, in association with immobilized CK 8 (+CK 8) or free in solution (Control), was activated with 10 nM sct-PA at 22 °C. Reactions were terminated by the addition of 10 μM PPACK at the times (in min) indicated at the bottom of each lane. The contents of each well were recovered in SDS and subjected to SDS/PAGE on 8% gels. Radioactive gels were imaged with a Phosphorimager. Incubations conducted for 60 min in the absence of sct-PA are labelled 60-. Aprotinin (10 μM) was present in each well through the entire incubation.

Activation of immobilized CK 8-associated plasminogen as determined by fluorescent substrate hydrolysis

The effects of CK 8 on plasminogen activation were characterized using immobilized CK 8 and the fluorescent plasmin substrate, VLK-AMC. In these experiments, various concentrations of plasminogen were incubated with immobilized CK 8 for 1 h at 22 °C. The wells were washed and activation was initiated by the addition of sct-PA (10 nM) and VLK-AMC (5 mM). The amount of plasminogen bound to the CK 8 had been determined in previous radioligand binding experiments. Thus, we could compare the rates of activation of identical amounts of CK 8-associated plasminogen and plasminogen in solution, in BSA-coated wells. Figure 6 shows that plasminogen activation by sct-PA was accelerated when the plasminogen was CK 8-associated. For the three concentrations of plasminogen studied, the velocity of VLK-AMC hydrolysis was 5–10 times greater for plasminogen that was initially CK 8-associated, compared with plasminogen in solution. Since plasmin that is CK 8-associated hydrolyses VLK-AMC at a decreased rate, the rate of plasminogen activation may have been as much as 20 times greater in the CK 8-containing wells.

SDS/PAGE analysis of ^{125}I -plasminogen activation by sct-PA

In continuous assays (activator, plasminogen and plasmin substrate present in the same solution), plasmin substrates can affect the rate of plasminogen activation [25,26]. Thus, SDS/PAGE experiments were performed to confirm that CK 8 accelerates the rate of [^{125}I]-plasminogen activation by sct-PA. ^{125}I -[Glu¹]-plasminogen (1 μM) was incubated with immobilized CK 8 for 1 h at 22 °C. After washing the wells, 10 nM sct-PA and 10 μM aprotinin were added. At various times, the sct-PA inhibitor, PPACK (10 μM), was added to stop the reaction. The contents of the wells were solubilized with SDS and subjected to SDS/PAGE. ^{125}I -[Glu¹]-plasminogen activation was detected as conversion of the single-chain form of the protein into the two-chain form (apparent masses of 60 and 35 kDa). Figure 7 shows that the majority of the CK 8-associated ^{125}I -[Glu¹]-plasminogen

was converted into plasmin within 5 min. By contrast, the identical amount of ^{125}I -[Glu¹]plasminogen remained primarily in the zymogen form when incubated with 10 nM sct-PA in BSA-coated wells. No activation was observed when CK 8-associated plasminogen was incubated for 1 h at 22 °C without sct-PA (Figure 7, lane 60 –).

Equivalent experiments were performed with [Lys⁷⁸]plasminogen and sct-PA. In the absence of CK 8, the [Lys⁷⁸]plasminogen was activated at a more rapid rate compared with [Glu¹]plasminogen, as expected. When the [Lys⁷⁸]plasminogen was initially CK 8-associated, the rate of activation was substantially increased. Almost all of the plasminogen was converted into the two-chain form in 5 min (results not shown). These studies and the experiments with BT20 cell-conditioned medium demonstrate that the effects of CK 8 on plasminogen activation are not restricted to the closed plasminogen conformation adopted selectively by [Glu¹]plasminogen.

DISCUSSION

Plasmin activity is controlled locally by the action of plasminogen activators, such as t-PA and u-PA, and by plasmin inhibitors, including α_2 -antiplasmin and α_2 -macroglobulin [1,2]. A second level of control is imposed by proteins which bind plasminogen via kringle domain lysine-binding sites. These proteins, which include soluble factors, extracellular matrix components and plasma membrane receptors, alter the rate of plasminogen activation by t-PA and u-PA [1,2,27,28]. The same factors also decrease the reactivity of bound plasmin with inhibitors. Thus, kringle domain-dependent interactions profoundly influence the concentration of available plasmin in various micro-environments.

In the present study, we demonstrated the presence of soluble CK 8-containing complexes in the conditioned medium of breast carcinoma cells, confirming previous studies [18]. The soluble CK 8 bound plasminogen and enhanced the rate of plasminogen activation by t-PA. In experiments with purified immobilized CK 8, we demonstrated that CK 8 has the capacity to bind both t-PA and plasminogen. Thus, CK 8 may promote plasminogen activation on the cell surface and in the pericellular spaces surrounding breast cancer cells, *in vivo*.

Plasminogen exists in at least two conformations that are differentially activated [1,23,24]. In the presence of physiological concentrations of Cl^- , [Glu¹]plasminogen exists primarily in the 'closed' conformation which is relatively resistant to activation [29]. [Glu¹]plasminogen is converted into the more readily activated 'open' conformation by plasmin-mediated cleavage of the N-terminal peptide to yield [Lys⁷⁸]plasminogen or by binding ω -amino acids such as ϵ -ACA [2,24,29]. Proteins that bind to the kringle domains may also convert [Glu¹]plasminogen into the open conformation and thereby promote [Glu¹]plasminogen activation [30]. By contrast, the conformation of [Lys⁷⁸]plasminogen is minimally affected by lysine-binding interactions [1,24]. In our experiments, with BT20 cell-conditioned medium and purified CK 8, an increased rate of plasminogen activation was observed with both [Glu¹]- and [Lys⁷⁸]plasminogen, suggesting that plasminogen conformational change is not exclusively responsible for the increased rate of activation. An alternative model is that which has been proposed for fibrin [3]. t-PA and plasminogen bind to fibrin, forming a ternary complex in which the plasminogen is activated more readily. We hypothesize that a similar ternary complex forms with CK 8; however, based on the studies completed to date, we cannot rule out the possibility that CK 8 functions primarily as

an enzyme (t-PA) modulator without requiring plasminogen binding for enhanced activation.

Recently, we identified CK 8 as a candidate plasminogen receptor on several epithelial and carcinoma cell lines [12]. While most of the cellular CK 8 is contained within highly insoluble filaments, CK 8 may also exist as a component of soluble complexes intracellularly and in the extracellular spaces [15,18,19]. Intracellular soluble cytokeratin is in the form of heteropolymers; little or no cytokeratin exists as complexes smaller than a tetramer [31]. Bachant and Klymkowsky [32] subjected soluble cytokeratins from *Xenopus* oocytes to molecular exclusion chromatography and found that the majority of the protein eluted with an apparent mass of 750 kDa, while a smaller amount eluted at 150 kDa. Our chromatography analysis of CK 8 released by tumour cells showed similarly sized complexes, although some of the CK 8 also eluted in the void volume. At the present time, we do not understand the relationship of released CK 8 to soluble and insoluble forms of intracellular cytokeratin; however, the CK 8-containing complexes released from the BT20 cells are probably equivalent to Tissue Polypeptide Antigen. The ability of tumour-secreted, soluble CK 8 to enhance plasminogen activation suggests that Tissue Polypeptide Antigen may influence fibrinolysis *in vivo*.

Expression of CK 8 is usually restricted to simple epithelia; however, numerous studies have shown that CK 8 is aberrantly expressed in malignant cells [33–35]. Aberrant expression of CK 8 may correlate with an invasive phenotype. In transitional cell carcinoma and squamous cell carcinoma, aberrant expression of CK 8 is localized to the tumour invasion front [36,37]. In malignant melanoma, aberrant expression of CK 8 is correlated with an increase in tumour invasiveness, *in vitro* [33]. Most significantly, mouse L fibroblasts, which lack CK 8, show increased motility and penetration of Matrigel after transfection with CK 8/CK 18 [38]. Motility and cellular invasion through Matrigel are processes that are promoted by cell-surface-associated plasmin. The studies presented here suggest a model that may partially explain the correlation of CK 8 expression with cellular invasiveness. We propose that the small fraction of total cellular CK 8, which is expressed on the outer cell surface, may promote cellular invasiveness by enhancing proteinase activation in the pericellular spaces.

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Cell-surface Cytokeratin 8 Is the Major Plasminogen Receptor on Breast Cancer Cells and Is Required for the Accelerated Activation of Cell-associated Plasminogen by Tissue-type Plasminogen Activator*

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Cytokeratin 8 (CK 8) has been identified on the external surfaces of viable, unpermeabilized epithelial cells (Hembrough, T. A., Vasudevan, J., Allietta, M. M., Glass, W. F., and Gonias, S. L. (1995) *J. Cell Sci.* 108, 1071–1082). In this study, we demonstrated that CK 8 is the major plasminogen-binding protein in plasma membrane fractions isolated from three breast cancer cell lines, BT20, MCF-7, and MDA-MB-157. To assess the function of CK 8 as a plasminogen receptor, monoclonal antibody 1E8 was raised against the carboxyl-terminal 12 amino acids of CK 8. The 1E8 epitope was present on the external surfaces of breast cancer cells, as determined by immunofluorescence microscopy. ^{125}I -1E8 bound to MCF-7 cells; the maximum binding capacity (1.5×10^6 sites per cell) was comparable with that determined for plasminogen. When MCF-7 cells were incubated with Fab fragments of 1E8, specific ^{125}I -plasminogen binding was decreased up to 82%. Specific plasminogen binding was decreased up to 67%, even when the unbound 1E8 Fab was removed by washing the cells prior to adding ^{125}I -plasminogen. Preincubation with 1E8 Fab decreased plasminogen binding to BT20 and MDA-MB-157 cells, although to a lesser extent than with MCF-7 cells. Plasminogen activation by tissue-type plasminogen activator was greatly accelerated, due to a large decrease in K_m , when the plasminogen was bound to MCF-7 cells. Pretreatment with 1E8 Fab decreased the rate of plasminogen activation by up to 83%, implicating CK 8 in the MCF-7 cell-accelerated reaction. These studies identify cell-surface CK 8 as a major plasminogen receptor in breast cancer cells and as a required component for the rapid activation of cell-associated plasminogen by tissue-type plasminogen activator.

Cancer invasion and metastasis are promoted by proteinases that are activated on the tumor cell surface and in the pericellular spaces. These proteinases digest basement membrane and extracellular matrix components, allowing tumor cell penetration through tissue (1). In breast cancer, cellular expression of the serine proteinase, urokinase plasminogen activator

(u-PA),¹ has been correlated with an aggressive, malignant phenotype (2, 3). This may reflect the ability of cell-associated u-PA to activate plasminogen that, in turn, digests glycoprotein components of the extracellular matrix and may activate other proteinases (4, 5). A second plasminogen activator, tissue-type plasminogen activator (t-PA), also binds to cell surfaces and activates plasminogen (6). t-PA may substitute for u-PA in promoting tumor cell invasion (7).

The cellular receptor for u-PA has been cloned and characterized (8, 9). uPA receptor is a glycosylphosphatidylinositol-anchored membrane protein that binds u-PA with moderately high affinity ($K_D \sim 1.0$ nM). Cellular binding sites for t-PA and plasminogen have also been identified; however, the biochemical nature of these sites remains more vague. Breast cancer cells *in vitro* bind plasminogen in a specific and saturable manner (10, 11). As is typical of most plasminogen/cellular interactions, the binding affinity is modest ($K_D \sim 1.0$ μM); however, the binding capacity is high ($B_{\text{max}} \sim 10^6$ sites per cell). Occupancy of breast cancer cell plasminogen-binding sites *in vivo* probably depends on the concentration of plasminogen in the surrounding tissue, which may be quite high since the plasma concentration of plasminogen is about 1–2 μM .

Plasminogen is activated more readily by u-PA and t-PA when both enzyme and substrate are bound to the surfaces of certain cell types (6, 12–14). Plasmin that is cell-associated reacts very slowly with α_2 -antiplasmin and α_2 -macroglobulin, which are rapid inhibitors of solution-phase plasmin (15, 16). Thus, the identification and characterization of major cellular binding sites for plasminogen is important for understanding the role of plasmin in tumor cell invasion and other processes that require cell-surface proteolytic activity.

Plasminogen binding to cellular receptors and other macromolecules, including fibrin and specific extracellular matrix proteins, is mediated by its kringle domains, three of which (K1, K4, and K5) express affinity for lysine (17–19). The highest affinity interaction usually involves K1 and proteins with carboxyl-terminal lysines (19, 20). Several plasminogen receptors have been identified in eukaryotic cells. Annexin II, which was identified as an endothelial cell plasminogen receptor, lacks a carboxyl-terminal lysine in its native form and thus requires proteolytic modification by Lys-specific proteinases in order to acquire plasminogen-binding activity (21, 22). α -Enolase, which was identified as a plasminogen receptor in U937

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¹ The abbreviations used are: u-PA, urokinase plasminogen activator; t-PA, tissue-type plasminogen activator; CK 8, cytokeratin 8; eACA, ϵ -amino caproic acid; BSA, bovine serum albumin; CPB, carboxypeptidase B; PBS, phosphate-buffered saline; PAGE, polyacrylamide gel electrophoresis; RFU, relative fluorescence units; VLK-AMC, D-Val-L-Leu-L-Lys-5-aminomethylcoumarin.

monocytoid cells, contains a carboxyl-terminal lysine in its intact form (20). Both α -enolase and annexin II have been demonstrated on the external surfaces of cultured cells, using antibody-based technologies (20, 21); however, the level of expression of cell-surface α -enolase is sufficient to account for only about 10% of the plasminogen binding capacity of U937 cells (23).

Cytokeratin 8 (CK 8) is an intermediate filament protein that polymerizes with CK 18 to form a component of the cytoskeleton in simple epithelia and many epithelial cell-derived neoplasms. CK 8 interacts extensively with the internal leaflet of the plasma membrane and is, therefore, one of the major components recovered in the plasma membrane fraction when epithelial cells are subjected to subcellular fractionation procedures (10). CK 8 is unique among cytokeratins in that the intact structure includes a carboxyl-terminal lysine. In a recent study, we demonstrated that CK 8 is the primary plasminogen-binding protein in the plasma membrane fraction isolated from hepatocytes (10). We then demonstrated, by immunoelectron microscopy and immunofluorescence microscopy, that CK 8 is present on the external surfaces of intact, unpermeabilized hepatocytes, hepatocellular carcinoma cells, and breast cancer cells, confirming previous studies (24, 25) and identifying CK 8 as a candidate plasminogen receptor.

The purpose of the present study was to determine (i) whether cell-surface CK 8 binds plasminogen; (ii) whether CK 8 contributes substantially to the total plasminogen binding capacity of breast cancer cells; and (iii) whether cell-associated CK 8 promotes plasminogen activation. To accomplish these goals, we prepared a monoclonal antibody (1E8) specific for the carboxyl-terminal 12 amino acids of intact CK 8, which was considered the most likely plasminogen-binding site within the CK 8 structure. We then prepared highly purified Fab fragments of 1E8. This was an important step since the primary structure of all mouse and human IgG isotypes includes carboxyl-terminal Lys residues (26), which, unless exposed to plasma carboxypeptidases, bind plasminogen in solution (27, 28). The results presented here demonstrate that CK 8 is the major plasminogen-binding protein in the plasma membrane fraction of breast cancer cells, the primary protein responsible for the majority of the specific binding of plasminogen to intact breast cancer cells in culture, and a required cellular component for the accelerated activation of cell-associated plasminogen by t-PA.

EXPERIMENTAL PROCEDURES

Materials—Leupeptin and L-trans-epoxysuccinyl-leucylamido(4-guanidinyl)butane (E-64) were from Boehringer Mannheim. Aprotinin, chloramine T, ϵ -aminocaproic acid (ϵ ACA), phenylmethylsulfonyl fluoride, and bovine serum albumin (BSA) were from Sigma. Porcine pancreatic carboxypeptidase B (CPB) was from Worthington. Na¹²⁵I was from Amersham Int. D-Val-L-Leu-L-Lys-5-aminomethylcoumarin (VLK-AMC) was from Enzyme Systems Products (Livermore, CA). IODO-BEADS were from Pierce. Earle's balanced salt solution was from Life Technologies, Inc.

Proteins and Antibodies—[Glu¹]Plasminogen was purified from human plasma by the method of Deutsch and Mertz (29). Single-chain tissue-type plasminogen activator (t-PA) was purchased from American Diagnostica. Monoclonal antibody PCK-26, which recognizes CK 5, CK 6, and CK 8, was from Sigma. Of these cytokeratins, only CK 8 is expressed by breast cancer cells (30).

A polypeptide corresponding to the 12 carboxyl-terminal amino acids of human CK 8, preceded by an amino-terminal cysteine, CKLVSESS-DVLPK, was synthesized using Fmoc (N-(9-fluorenyl)methoxycarbonyl) chemistry on a Gilson AMS 422 multi-peptide synthesizer and purified by high performance liquid chromatography on a Poros flow-through column (PerSeptive Biosystems, MA). The peptide was cross-linked via its amino-terminal cysteine to maleimide-activated keyhole limpet hemocyanin (Pierce) and used to immunize A/J mice (Jackson Labs, ME). Antibody titers were determined using the same peptide cross-linked to

BSA. The mouse with the highest titer was given a final intrasplenic booster. Two days later, spleen cells were harvested and fused with SP2/0 mouse myeloma cells. These cells were selected in HAT-containing medium and cloned.

Eighteen clones generated antibodies that specifically bound CK 8. These antibodies were further screened for ability to detect CK 8 by immunofluorescence microscopy and Western blot analysis. One clone (1E8) was selected for subcloning. Ascites was generated by expanding the subclone of 1E8 (1E8-C6-B4) in CAF1 mice (Jackson Labs, ME), and antibody was purified by Protein A chromatography. Antibody 1E8 isotype was an IgG_{2b}.

Generation of 1E8 Fab Fragments—Fab fragments of antibody 1E8 were generated using the Immunopure Fab Preparation Kit (Pierce). Briefly, 5 mg of antibody were incubated with 1 ml of papain-agarose for 2 h at 37 °C. Digested antibody was separated from papain-agarose and subjected to protein A-Sepharose chromatography. The flow-through was collected in 1-ml fractions and analyzed by SDS-PAGE. Fractions containing Fab fragments were pooled, aliquoted, and stored at -20 °C until needed. Intact antibody did not contaminate the final Fab preparations, as determined by Coomassie staining of gels that contained up to 20 μ g of purified Fab per lane. For some experiments, 1E8 Fab preparations were further processed by incubation with CPB-Sepharose for 12 h at 25 °C, to remove any residual carboxyl-terminal lysine residues (as might have been present due to trace contamination with Fc domain). The CPB-Sepharose was prepared by coupling 5 mg of CPB/1 g of CNBr-activated Sepharose.

Cell Lines and Tissue Culture—All cell lines were obtained from the ATCC (Rockville, MD). The breast cancer cell lines, MCF-7 and MDA-MB-157, and the fibroblast cell line, AKR-2B, were cultured in Dulbecco's modified Eagle's medium supplemented with 10% fetal bovine serum, 2 mM glutamine, 100 units/ml penicillin, and 100 mg/ml streptomycin. BT20 breast cancer cells were cultured in RPMI 1640, supplemented as above. Cells were typically passaged by trypsin/EDTA treatment and gentle scraping. In order to minimize the effects of trypsin on cell-surface proteins, cultures were maintained for at least 2 days after passaging before performing experiments.

Subcellular Fractionation—Confluent monolayers of breast cancer cells ($3-6 \times 10^7$ cells) were harvested by gentle scraping into 5 mM EDTA and pelleted at $200 \times g$. Whole cell extracts (W fraction) were obtained by Dounce homogenization in the presence of 10 μ M aprotinin, 1 mM phenylmethylsulfonyl fluoride, 1 mM EDTA, 10 μ M leupeptin, and 0.2 μ g/ml E-64. The W fraction was centrifuged at $250 \times g$ for 20 min in an Eppendorf microcentrifuge. The resulting pellet consisted of nuclei and unhomogenized cells (N fraction). The supernatant was centrifuged at $1250 \times g$ for 20 min. The resulting pellet was enriched in plasma membrane but partially contaminated with mitochondria, whereas the supernatant consisted of cytoplasm and organelles, including mitochondria (C fraction). The plasma membrane-enriched pellet was resuspended in 1.45 M sucrose (400 μ l) and overlaid with 0.25 M sucrose in a 500- μ l airfuge tube. The step gradient was centrifuged at $55,000 \times g$ in an airfuge for 45 min. Enriched plasma membranes (P fraction) were collected from the interface of the two sucrose solutions (31).

SDS-PAGE, Western Blotting, and Plasminogen Overlay Assays—Subcellular fractions from breast cancer cells were subjected to SDS-PAGE and electrotransferred to polyvinylidene difluoride membranes (Millipore) using a Hoefer Transphor apparatus (2 h, 0.5 amp). In some studies, the transferred proteins were stained with 0.2% (w/v) Coomassie Blue R-250 (Bio-Rad). In plasminogen overlay experiments, the membranes were blocked with 5% nonfat dried milk, rinsed twice with 20 mM sodium phosphate, 150 mM NaCl, 0.1% (v/v) Tween 20, pH 7.4 (PBS-T), and then incubated with ¹²⁵I-plasminogen (10 nM) and aprotinin (10 μ M), in the presence and absence of 10 mM ϵ ACA or a 50-fold molar excess of non-radiolabeled plasminogen. To determine radioligand binding, the blots were rinsed three times for 15 min in PBS-T, dried, and analyzed using a PhosphorImager. For Western blot analyses, blocked membranes were incubated sequentially with a 1:500 dilution of CK 8-specific antibody (PCK-26 or 1E8), horseradish peroxidase-labeled goat anti-mouse monoclonal antibody, and diaminobenzidine.

¹²⁵I-1E8 Binding to MCF-7 Cells—Antibody 1E8 was radiolabeled using IODO-BEADS (Pierce). The specific activity was 1–2 μ Ci/ μ g. Confluent MCF-7 cells were subcultured into 48-well plates and grown for 48 h. Increasing concentrations of ¹²⁵I-1E8 (0.02–1.0 μ M), in Earle's balanced salt solution, 10 mM HEPES, 10 mg/ml BSA, pH 7.4 (EHB), were incubated with the cells for 2 h at 4 °C. The cells were then rinsed three times with EHB and once with PBS. Cell-associated radioactivity was recovered in 1.0% SDS, 0.1 M NaOH and measured in a γ -counter. For concentrations of ¹²⁵I-1E8 up to 0.2 μ M, nonspecific binding was determined by competition with a 50-fold molar excess of non-radiola-

beled 1E8. Nonspecific binding was plotted as a function of ^{125}I -1E8 concentration and extrapolated to higher concentrations by linear regression. Specific ^{125}I -1E8 binding was then determined, at each concentration, by subtracting the nonspecific binding derived from the standard curve. Specific binding isotherms were fit to the equation for a rectangular hyperbola by nonlinear regression and analyzed by Scatchard transformation.

^{125}I -1E8 Binding to Purified CK 8—Rat hepatocyte CK 8 was purified by the method of Achtstaetter *et al.* (32). In the final step of this procedure, CK 8 is eluted from DEAE-Sephacel in a buffer that contains 8.0 M urea. The purified CK 8, at a concentration of 15 $\mu\text{g}/\text{ml}$, was diluted 1:3 with PBS and incubated in 48-well tissue culture plates for 1.5 h at 37 °C. The plates were rinsed three times and blocked with 10 mg/ml BSA for 1.5 h at 37 °C. ^{125}I -1E8 binding was studied using the method described for the cell cultures in the previous section.

^{125}I -Plasminogen Binding to Breast Cancer Cells in the Presence of 1E8 Fab—In order to determine the contribution of cell-surface CK 8 to the total plasminogen binding capacity of breast cancer cells, competition binding experiments were performed. 1E8 Fab (0.5–8.0 μM) was preincubated with MCF-7 cells for 2 h at 4 °C. In some experiments, the cultures were washed three times with EHB to ensure that all unbound 1E8 Fab was removed. In other studies, the 1E8 Fab was allowed to remain in the cultures. ^{125}I -Plasminogen (0.2 μM) was then added in the presence and absence of 10 mM ϵACA or a 50-fold molar excess of unlabeled plasminogen, for 1 h at 4 °C. Unlabeled plasminogen and ϵACA are equally effective at displacing ^{125}I -plasminogen from specific cellular binding sites (12, 13). At the conclusion of an incubation, the cultures were washed three times. Cell-associated radioactivity was recovered in SDS/NaOH and measured in a γ -counter. For the protocol in which unbound 1E8 Fab was not removed by washing prior to adding ^{125}I -plasminogen, the 1E8 Fab was always pretreated with CPB-Sepharose. In control experiments, the effects of monoclonal antibody 1D7 Fab on ^{125}I -plasminogen binding to MCF-7 cells was studied. 1D7 is specific for human α_2 -macroglobulin. ^{125}I -Plasminogen binding was also studied in cultures of BT20 cells, MDA-MB-157 cells, and AKR-2B fibroblasts, with and without prior 1E8 Fab treatment. Fibroblasts do not express CK 8 (this was confirmed by Western blotting with PCK-26 and 1E8) and thus cannot bind 1E8 Fab in a specific manner.

Plasminogen Activation by t-PA—Increasing concentrations of plasminogen (0.05–1.0 μM) were incubated with MCF-7 cells or in wells without cells for 1 h at 22 °C. The MCF-7 cell cultures were washed so that only cell-associated plasminogen remained. t-PA (2 nM) and the plasmin-specific fluorescent substrate, VLK-AMC (0.5 mM), were added simultaneously to the MCF-7 cell cultures and to the wells without cells. Plasminogen activity was detected by continuous monitoring (30-s intervals) of fluorescence emission using a Cytofluor 2350 fluorescent plate reader (Millipore). The excitation wavelength was 380 nm, and the emission wavelength was 480 nm (5-nm slit widths). Curves of fluorescence against time were transformed using a first derivative function so that the resulting plots showed the concentration of active plasmin against time. Amounts of plasminogen, which bound to the MCF-7 cells, were determined separately, by performing equivalent incubations with ^{125}I -plasminogen. The velocity of VLK-AMC hydrolysis (0.5 mM) by MCF-7 cell-associated plasmin was decreased by $45 \pm 3\%$ ($n = 4$) compared with solution-phase plasmin; the presented graphs were not corrected for this difference in substrate hydrolysis rate. No VLK-AMC hydrolysis was observed when either plasminogen or t-PA were omitted from the reaction.

To determine whether CK 8 affects the kinetics of plasminogen activation by t-PA on the cell surface, MCF-7 cells were preincubated for 1 h at 22 °C with increasing concentrations of 1E8 Fab (1.0–8.0 μM) or with vehicle. After washing the cultures, 1.0 μM plasminogen was added for 1 h. After washing the cells again, t-PA (2 nM) and VLK-AMC (0.5 mM) were added simultaneously. Plasminogen activation was determined by monitoring fluorescence emission.

Immunofluorescence Microscopy—BT20 and MCF-7 cells were passaged onto 30-mm glass coverslips and grown for at least 48 h. The cells were washed with EHB buffer and incubated with purified 1E8 at 1/200 dilution for 2 h at 4 °C. The cells were then washed three times with EHB, incubated with Texas Red-labeled goat anti-mouse IgG (1/1000 dilution) for 2 h at 4 °C, rinsed three times again, and fixed in ice-cold paraformaldehyde. Cellular immunofluorescence was imaged using an Olympus 3H2 Microscope. In control experiments, mouse nonimmune IgG was substituted for primary antibody or primary antibody was omitted.

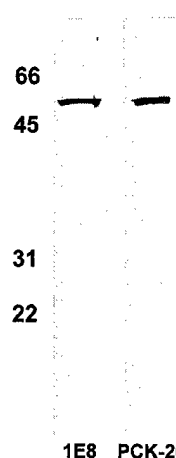


FIG. 1. CK 8 specificity of antibody 1E8. BT20 whole cell lysate (100 μg) was subjected to Western blot analysis using the well characterized CK 8-specific antibody, PCK-26, and the newly generated antibody, 1E8. Molecular mass standards (in-kDa) are shown.

RESULTS

Characterization of Monoclonal Antibody 1E8—Whole cell extracts from BT20 breast cancer cells were subjected to SDS-PAGE and Western blot analysis using the newly generated monoclonal antibody, 1E8. Only a single protein immunoreacted with 1E8. This protein was CK 8, as determined by its molecular mass (55 kDa) and immunoreactivity with antibody PCK-26 (Fig. 1). In control experiments, identical amounts of protein from whole cell extracts of AKR-2B cells, which lack CK 8, were subjected to Western blot analysis with antibody 1E8. No immunoreactivity was observed (results not shown).

We previously performed indirect immunofluorescence microscopy experiments, using antibodies AB 6.01 and M20, which recognize CK 8, and demonstrated the presence of CK 8 or a CK 8-like protein on the external surfaces of intact, unpermeabilized breast cancer cells (10). To determine whether the carboxyl terminus of CK 8, which we considered the most likely plasminogen-binding site, was exposed on the surfaces of breast cancer cells, immunofluorescence microscopy studies were performed with antibody 1E8. Fig. 2 shows that antibody 1E8 bound to live, nonpermeabilized BT20 cells, forming a diffuse and punctate pattern, identical to that seen with other CK8-reactive antibodies (PCK-26, AB 6.01) (10). All of the cells in each preparation showed positive immunofluorescence, irrespective of whether they were in clusters or isolated. When primary antibody was omitted or when mouse nonimmune IgG was substituted for antibody 1E8, no immunostaining was observed. Equivalent results were obtained with MCF-7 cells (results not shown); however, AKR-2B fibroblasts were immunonegative with antibody 1E8, as expected (data not shown).

Plasminogen Overlay Assays—In our previous study (10), we performed plasminogen overlay assays and demonstrated that CK 8 is the major plasminogen-binding protein in the P fraction (plasma membranes) of rat hepatocytes. Fig. 3 shows that similar results were obtained when three separate breast cancer cell lines were analyzed. In the P fraction from each cell line, the major plasminogen-binding protein had an apparent mass of 55 kDa, identical to that of CK 8. The MDA-MB-157 cell P fraction showed a second, plasminogen-binding species, with an apparent mass of 35 kDa. This 35-kDa band was also present as a minor component in the P fraction from the MCF-7 cells. ^{125}I -Plasminogen binding to the 55- and 35-kDa bands was completely inhibited when ϵACA or excess unlabeled plasminogen was added (results not shown).

In the whole cell (W) extract from all three breast cancer cell lines, the 55-kDa band was the major plasminogen-binding

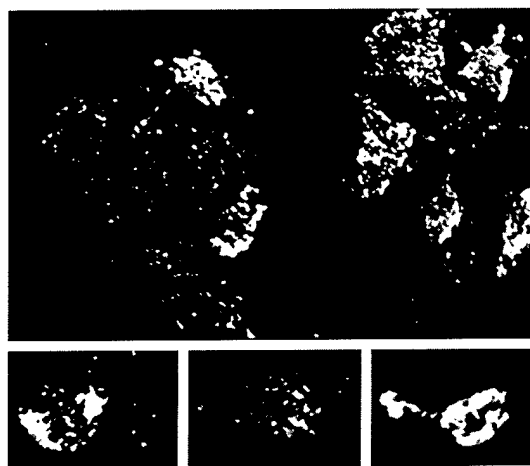


FIG. 2. Indirect immunofluorescence microscopy of BT20 breast cancer cells. Viable, nonpermeabilized BT20 breast cancer cells were immunolabeled with monoclonal antibody 1E8, followed by Texas Red-labeled goat anti-mouse IgG. The *top panel* shows a field with two clusters of BT20 cells. The *three lower fields* show isolated cells within the preparation. All cells displayed a similar pattern of diffuse, punctate cell surface immunolabeling.

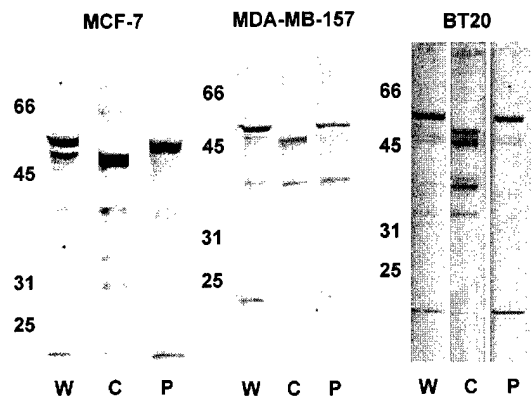


FIG. 3. ^{125}I -Plasminogen overlay assays of breast cancer cell subcellular fractions. Subcellular fractions (W, whole cell extract; C, cytoplasm; P, plasma membrane) from the three breast cancer cell lines were subjected to SDS-PAGE, blotted onto polyvinylidene difluoride membranes, and incubated with 10 nM ^{125}I -plasminogen. Binding was detected by PhosphorImager analysis. Molecular mass standards (in kDa) are shown.

component. The prominent appearance of the 55-kDa band in the W fractions distinguished the breast cancer cells from hepatocytes; in the hepatocyte W fraction, CK 8 was a minor plasminogen-binding component (10). The 55-kDa band was excluded from the breast cancer cell cytoplasmic fractions (C), as would be expected for CK 8.

To confirm that the 55-kDa band observed in the plasminogen overlay assays was CK 8, the identical BT20 subcellular fractions were subjected to Western blot analysis with antibody PCK-26. The antibody detected large amounts of CK 8 in both the W and P fractions, while a greatly reduced level of antigen was detected in the C fraction (Fig. 4). The mobility of the major band detected in the Western blot analysis coincided exactly with the mobility of the 55-kDa band in the plasminogen overlay assays.

Specific Binding of Antibody 1E8 to MCF-7 Cells—Radioiodinated antibody 1E8 bound to MCF-7 cells in a specific, saturable manner. A representative binding isotherm is shown in Fig. 5. An unexpected finding in this and two other equivalent studies was that the results transformed into apparently linear Scatchard plots. While not conclusive, this result suggests that each antibody engages only a single CK 8 epitope. The K_D for

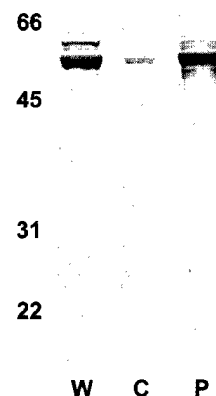


FIG. 4. Western blot analysis of BT20 subcellular fractions. The identical BT20 breast cancer cell subcellular fractions, shown in Fig. 3, were subjected to Western blot analysis with antibody PCK-26. Molecular mass standards (in kDa) are shown.

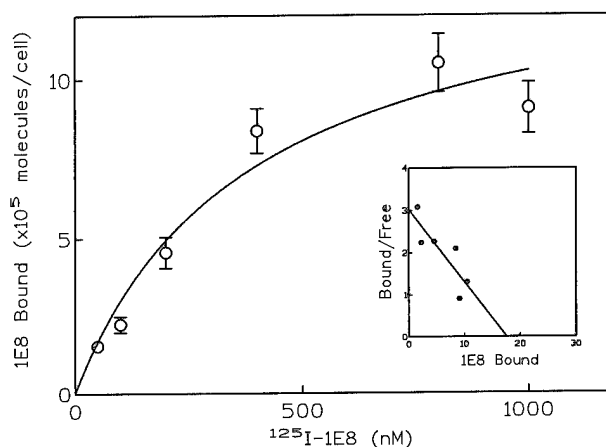


FIG. 5. Specific binding of ^{125}I -1E8 to MCF-7 breast cancer cells. Increasing concentrations of ^{125}I -1E8 were incubated with MCF-7 cells in the presence and absence of excess unlabeled 1E8. Specific binding is shown. Each point represents the average $\pm$ S.E. of four replicate determinations in a single study, which is representative of three separate experiments. The Scatchard transformation is shown in the *inset*.

1E8 binding to MCF-7 cells was $0.4 \pm 0.1 \mu\text{M}$ and the B_{max} was $1.5 \pm 0.5 \times 10^6$ sites per cell ($n = 3$). The B_{max} for 1E8 is comparable with that determined for plasminogen binding to the same cell type (10).

In control experiments, binding of intact ^{125}I -1E8 to purified, immobilized CK 8 was studied. ^{125}I -1E8 bound specifically and saturably to the CK 8, whereas no binding was observed in BSA-coated wells in two separate experiments. The data transformed into linear Scatchard plots ($r > 0.95$) and a K_D of $0.24 \mu\text{M}$ was derived (results not shown).

1E8 Fab Fragments Block Plasminogen Binding to Breast Cancer Cell Lines—The contribution of cell-surface CK 8 to the plasminogen binding capacity of breast cancer cells was studied using 1E8 Fab and MCF-7 cells, as a representative cell line. When 1E8 Fab was coinubated with ^{125}I -plasminogen in the MCF-7 cell cultures, specific radioligand binding was decreased and the extent of the decrease was 1E8 Fab concentration-dependent (Fig. 6). With the highest concentration of 1E8 Fab ($8 \mu\text{M}$), specific plasminogen binding was decreased by 82%.

In separate experiments, MCF-7 cells were preincubated with 1E8 Fab and then washed to remove unbound Fab prior to adding ^{125}I -plasminogen. It was anticipated that this protocol would decrease the level of observed competition since 1E8 Fab dissociation from the cell surface would be favored while the ^{125}I -plasminogen is present in the cultures. However, as shown

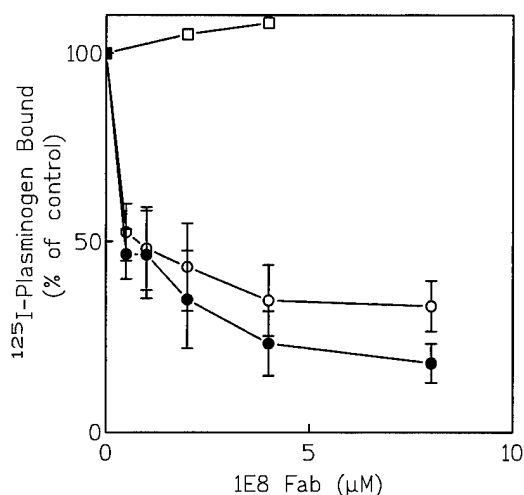


FIG. 6. 1E8 Fab inhibits ^{125}I -plasminogen binding to MCF-7 cells. 1E8 Fab was preincubated with MCF-7 or AKR-2B cells for 2 h at 4 °C. In the first protocol, ^{125}I -plasminogen was added to the MCF-7 cell cultures without first washing the cells so that unbound 1E8 Fab remained (●). In the second protocol, the MCF-7 cells were washed to remove unbound 1E8 Fab prior to adding ^{125}I -plasminogen (○). The AKR-2B cells were washed after incubation with 1E8 Fab and prior to adding the ^{125}I -plasminogen (□). Specific plasminogen binding is expressed as a percentage of that observed without 1E8 Fab treatment. The presented results, for the MCF-7 cells, show the mean $\pm$ S.E. for five separate experiments.

in Fig. 6, significant inhibition of specific ^{125}I -plasminogen binding was still observed. In cells that were pretreated with 8 μM 1E8 Fab, ^{125}I -plasminogen binding was decreased by 67%. In control experiments, no decrease in ^{125}I -plasminogen binding was observed when AKR-2B fibroblasts were pretreated with 1E8 Fab. Antibody 1D7 Fab had no effect on ^{125}I -plasminogen binding to MCF-7 cells, irrespective of whether the Fab was present during the incubation with plasminogen or washed-out prior to adding plasminogen (results not shown). The ability of 1E8 Fab to inhibit plasminogen binding to MCF-7 cells, even after the free Fab was removed by washing, confirms that the observed competition is due to blocking of plasminogen-binding sites on the cell surface and not a solution-phase interaction with ^{125}I -plasminogen.

Binding of ^{125}I -plasminogen to BT20 and MDA-MB-157 cells was studied after pretreating the cultures with 4 μM 1E8 Fab. The cells were washed prior to adding ^{125}I -plasminogen to remove unbound 1E8 Fab. As shown in Table I, specific ^{125}I -plasminogen binding to the BT20 cells was decreased, and the magnitude of the effect was only slightly less than that observed with MCF-7 cells. Decreased plasminogen binding was also observed with the MDA-MB-157 cells; however, the effectiveness of 1E8 Fab was not as great in this cell line. In control experiments, we studied the effects of 1E8 Fab on plasminogen binding to purified, immobilized CK 8. 1E8 Fab (4 μM) was incubated with the CK 8. The wells were then washed before adding ^{125}I -plasminogen. In two separate experiments, specific ^{125}I -plasminogen binding was decreased by 62 and 68%. Thus, the extent of competition observed in the BT20 and MCF-7 cell cultures was similar to that detected using the identical protocol, in a purified system that includes CK 8 as the exclusive plasminogen-binding protein.

MCF-7 Cells Enhance Plasminogen Activation by t-PA—To study plasminogen activation by t-PA, increasing concentrations of plasminogen were added to MCF-7 cell cultures and to wells without cells. The cell cultures were washed, so that only cell-associated plasminogen remained (less than 3% of the plasminogen originally added to the wells). The wells without cells were not washed. t-PA and VLK-AMC were then added simul-

TABLE I
Inhibition of ^{125}I -plasminogen binding to breast cancer cell lines by 1E8 Fab

All cultures were pretreated with 4 μM 1E8 Fab and then washed before adding plasminogen. The column labeled CK 8 shows the inhibition observed in wells coated with purified CK 8 (no cells). All values represent the mean $\pm$ S.E.

	BT20 (n = 3)	MDA-MB-157 (n = 3)	MCF-7 (n = 6)	CK 8 (n = 2)
% inhibition	53 $\pm$ 3	39 $\pm$ 3	64 $\pm$ 8	65 $\pm$ 3

taneously to each well. In the MCF-7 cell cultures, the velocities of plasminogen activation showed an initial lag phase lasting about 2 min, followed by a 5–7-min period when the velocities optimized and the first derivative functions (dRFU/dt) linearized. RFU indicates relative fluorescence units. The period between 2.5 and 7 min was used to derive the plasminogen activation rates shown in Fig. 7 (panel A).

In wells without cells, plasminogen activation proceeded without an apparent lag phase. Rates of plasminogen activation (determined in the 2.5–7-min time interval) were slightly decreased compared with the rates measured in cell cultures that were initially incubated with the identical concentrations of plasminogen. However, since the wells without cells were not washed before adding t-PA, the amount of available plasminogen was actually about 100-fold greater. Fig. 7, panel B, shows Lineweaver-Burk transformations of the activation data. In the transformations, the actual amount of available substrate (plasminogen) is plotted as opposed to the amount initially added to the wells. Levels of cell-associated plasminogen are converted into units of concentration by dividing the number of moles of bound plasminogen by the total incubation volume (100 μl). The most remarkable finding was a 2000-fold reduction in the K_m for the activation of cell-associated plasminogen (2 nM) compared with plasminogen in solution (4 μM). Although the K_m for plasminogen activation in solution is similar to previously reported constants (33, 34), this value should be interpreted cautiously since the plasminogen concentration range was selected to match the cell culture studies and is substantially lower than that required for optimal accuracy. The V_{max} for plasminogen activation by t-PA was decreased about 3-fold when the plasminogen was cell-associated.

In order to study the role of cell-surface CK 8 in promoting the activation of plasminogen by t-PA, MCF-7 cells were pretreated with increasing concentrations of 1E8 Fab. The cells were then washed and incubated with plasminogen. After a final wash, t-PA and VLK-AMC were added simultaneously, and fluorescence was monitored. In this assay, some 1E8 Fab probably dissociated from the cell surfaces during the 1-h incubation with plasminogen at 22 °C. Nevertheless, as shown in Fig. 8, preincubation with 1E8 Fab caused a concentration-dependent decrease in the ability of the cell cultures to promote plasminogen activation. After incubation with 8 μM 1E8 Fab, the velocity of plasminogen activation was decreased by 83 $\pm$ 6%.

DISCUSSION

Numerous studies have demonstrated that cell-associated plasmin and plasminogen activators promote tumor cell invasion in *in vitro* model systems (1, 35, 36). An increasing number of studies support the function of these same proteinases and their cellular receptors in tumor invasion and metastasis *in vivo*. For example, Mueller *et al.* (37) demonstrated that melanoma cells, when transfected to overexpress plasminogen activator inhibitor 2, form subcutaneous tumors that do not metastasize in *scid* mice, unlike the highly metastatic parent cell line. Evans and Lin (38) blocked implantation of intravenously

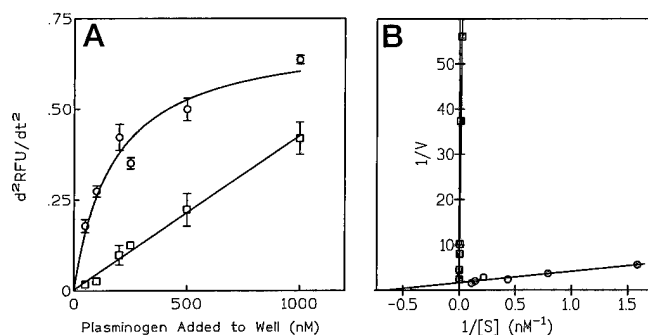


FIG. 7. Activation of MCF-7 cell-associated plasminogen by t-PA. Panel A shows rates of activation of MCF-7 cell-associated plasminogen (○) and plasminogen in solution (□) by 2 nM t-PA (mean $\pm$ S.E., $n = 4$). Plasminogen activation was detected by monitoring VLK-AMC hydrolysis. Activation rates were calculated from second derivatives (d^2RFU/dt^2) of the plots of fluorescence against time, beginning 2.5 min after adding the VLK-AMC. In panel A, the listed concentrations of plasminogen are the amounts that were added to the wells. In the cell cultures, the majority of the plasminogen was removed by washing before adding t-PA. Panel B shows Lineweaver-Burk transformations of the results presented in panel A. In panel B, the actual amount of plasminogen present in the well when the t-PA and VLK-AMC were added is shown.

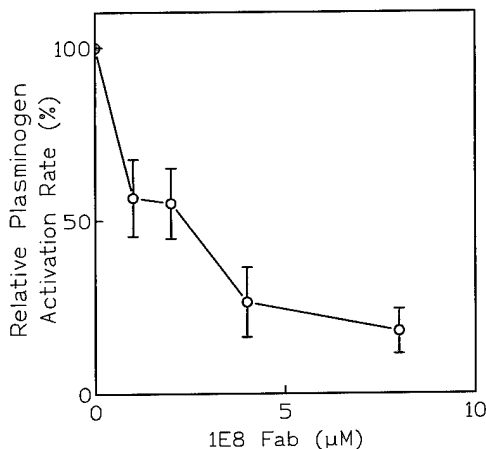


FIG. 8. Effects of 1E8 Fab on the activation of MCF-7 cell-associated plasminogen. 1E8 Fab was incubated with MCF-7 cells for 1 h at 22 °C. The cultures were washed, and plasminogen (1.0 μM) was added for 1 h. After washing again, t-PA and VLK-AMC were added, and fluorescence emission was monitored (mean $\pm$ S.E., $n = 3$). The relative plasminogen activation rate is plotted as a percentage of that observed with cells that were not 1E8 Fab-treated.

administered breast cancer cells, in the lungs of rats, by co-administering recombinant plasminogen activator inhibitor 2. Finally, Kobayashi *et al.* (39) demonstrated that urinary trypsin inhibitor, which neutralizes cell-associated plasmin, also inhibits cancer cell invasion through Matrigel *in vitro* and blocks formation of lung metastases by Lewis lung carcinoma cells *in vivo*. By contrast, the potent solution-phase plasmin inhibitors, α_2 -antiplasmin and α_2 -macroglobulin, which are ineffective against cell-associated plasmin, show no activity in the same cancer cell invasion assays (39). These studies emphasize the importance of identifying macromolecules responsible for plasminogen binding in cancer.

Our initial studies with rat hepatocytes identified CK 8 as a potential plasminogen receptor in epithelial cells (10). Since prior evidence for the presence of CK 8 on the outer surfaces of cells had been disputed, immunofluorescence and immunoelectron microscopy studies were performed. The fluorescence microscopy studies of hepatocytes and breast cancer cell lines showed that CK 8 is distributed uniformly on the surfaces of

viable, adherent cells and not restricted to a fraction of each population, such as injured cells (10). We confirmed that the cell preparations were, in fact, unpermeabilized and that the CK 8-specific antibodies recognized cell-surface CK 8 and not intracytoplasmic CK 8 by electron microscopy. However, since the epitopes recognized by commercially available CK 8-specific antibodies are uncharacterized, it was not possible to conclude that the region of CK 8 responsible for plasminogen binding is exposed on the cell surface. Thus, monoclonal antibody 1E8 was raised utilizing synthetic peptide technology. The similarity in the distribution of 1E8 immunofluorescence, compared with previously studied CK 8-specific antibodies (10), suggests that the carboxyl terminus of CK 8 is intact and available for protein-binding interactions on breast cancer cell surfaces. Furthermore, our binding studies with ¹²⁵I-1E8 provide an estimate of the amount of CK 8 on the outer surfaces of MCF-7 cells (1–2 million sites per cell). The density of CK 8 on the MCF-7 cell surface is sufficient to account for the high cellular binding capacity for plasminogen (10).

Competition binding experiments with ¹²⁵I-plasminogen and 1E8 were performed using two separate methods. The methods were designed to ensure that activity resulted from antibody binding to cell-surface CK 8 and not interaction with ¹²⁵I-plasminogen in solution. In early studies, we routinely screened antibody preparations for plasminogen-binding activity in solution by testing the ability of each antibody to inhibit ¹²⁵I-plasminogen binding to Lys-Sepharose. Various CK 8-specific monoclonal antibodies (1E8, PCK-26, AB 6.01, M20) bound plasminogen in solution, as determined by the Lys-Sepharose competition assay. 1E8 Fab preparations demonstrated little or no plasminogen binding activity, and after treatment with CPB-Sepharose, were entirely inactive. The variable amount of residual plasminogen binding activity in Fab preparations, without CPB-Sepharose treatment, may have reflected trace-level contamination with Fc domain or perhaps proteolytic modification of the Fab itself. When cell cultures were pre-treated with 1E8 Fab and then washed to remove free 1E8 Fab, before adding ¹²⁵I-plasminogen, any residual plasminogen binding activity that may have been associated with the Fab could only have increased the level of observed plasminogen binding to the cells. Thus, the 1E8 Fab "wash-out" protocol provided the most rigorous demonstration of receptor competition even though this method probably provided a minimum estimate of the contribution of CK 8 to the plasminogen binding capacity, due to 1E8 Fab dissociation from the cell surface during the incubation with plasminogen.

Of the three breast cancer cell lines studied, the greatest effects of 1E8 Fab on plasminogen binding were observed with MCF-7 cells. When CPB-Sepharose-treated 1E8 Fab was retained in the culture medium during the incubation with ¹²⁵I-plasminogen, binding was inhibited by up to 82%. Plasminogen binding was inhibited by 60–70% when the free 1E8 Fab was removed prior to adding ¹²⁵I-plasminogen. The difference between these two values suggests that 1E8 Fab may have partially dissociated from the cell surface after Fab washout but that substantial levels of cell-associated 1E8 Fab remained. In our studies comparing cell lines, 10% less competition was observed with BT20 cells and 25% less competition was observed with MDA-MB-157 cells, compared with the MCF-7 cells; however, at least with the BT20 cells, CK 8 still accounted for more than one-half of the plasminogen-binding sites. Since the Fab washout protocol was used in the experiments with MDA-MB-157 cells, it is quite possible that CK 8 accounts for more than 50% of the plasminogen-binding sites in this cell line as well. Thus, we conclude that CK 8 is a major plasminogen-binding protein in various breast cancer cell lines and may be

responsible for the great majority of the plasminogen-binding sites in some.

To demonstrate maximum inhibition of ^{125}I -plasminogen binding, we used high concentrations of 1E8 Fab; however, we still may not have entirely saturated available CK 8 binding sites for plasminogen. If the affinity of 1E8 Fab and intact antibody for CK 8 are equivalent ($\sim 0.4 \mu\text{M}$), then at equilibrium 1E8 Fab at 4 and $8 \mu\text{M}$ would be expected to occupy 91 and 95% of the available epitopes, respectively. If the affinity of 1E8 Fab for cell-surface CK 8 was reduced compared with intact antibody, then the degree of saturation would be less. In any case, the unoccupied CK 8 may be responsible for a significant fraction of the residual plasminogen binding, especially in experiments with the MCF-7 cells that were the most profoundly affected by 1E8 Fab.

Even though there are data to support an important role for u-PA in determining the metastatic potential of breast cancer cells (2, 3), we chose to assess the functional significance of plasminogen/breast cancer cell interactions by examining the rate of plasminogen activation by t-PA. We and others (6, 12, 13) have shown that only certain cell types, including hepatocytes, promote plasminogen activation by t-PA. We hypothesized that cell-surface CK 8 might be responsible for the previously demonstrated enhancement of plasminogen activation by t-PA in hepatocytes (12) and that CK 8 might promote plasminogen activation by t-PA in breast cancer cells. Our analysis of MCF-7 cells demonstrated that plasminogen activation by t-PA is greatly accelerated when the plasminogen is cell-associated. The increase in activation rate was attributed to a substantial decrease in K_m . From the data presented, it was not possible to conclude whether the enhanced rate of plasminogen activation requires only plasminogen binding to CK 8 or a concomitant interaction of t-PA with CK 8 or another surface binding site. In any respect, the 83% decrease in plasminogen activation rate after 1E8 Fab pretreatment demonstrates that CK 8 plays an essential role in promoting the activation of plasminogen by t-PA on the MCF-7 cell surface. The lag phase observed in the analysis of cell-associated plasminogen activation by t-PA provides suggestive evidence that t-PA may need to bind to a cell-surface site before it acquires optimal catalytic efficiency. If this is true, then one could postulate a model for enhanced plasminogen activation by CK 8 that is similar to that originally proposed for fibrin (40). In this model CK 8 would mediate the formation of a ternary complex in which the K_m for plasminogen activation is greatly decreased. In studies with purified CK 8, we recently demonstrated specific t-PA binding (41).

CK 8 can be aberrantly expressed in many nonepithelial cancers, including lymphomas, melanomas, gliomas, and sarcomas (42, 43). For many of these cancers, expression of CK 8 has been correlated with increased invasiveness *in vitro* and *in vivo*. When CK 8 is aberrantly expressed in squamous cell carcinomas, it is localized, by immunohistochemistry, primarily to the invasion front (44, 45). In malignant melanoma, *in vitro* invasiveness has been directly correlated with cellular expression of CK 8 (46). Finally, mouse L cells, a noninvasive CK 8-negative fibroblast cell line, becomes invasive after cotransfection with CK 8 and its co-polymer CK 18 (47). Based upon our work, we hypothesize that the increased invasiveness of CK 8-expressing cells may be partially explained by the small fraction of CK 8 that is available at the cell surface and competent to function as a plasminogen receptor.

The mechanism by which CK 8 is expressed on the cell surface is unknown. The sequence of CK 8 does not include a transmembrane domain; however, our unpublished prelimi-

nary data² suggest that cell-surface CK 8 is integrally associated with the plasma membrane. The alternate hypothesis is that CK 8, which is released by cells, binds to the external plasma membrane and then functions as an extrinsic receptor for plasminogen. In either case, the functional significance of CK 8, which is its ability to bind plasminogen and promote plasminogen activation on the tumor cell surface, is the same. We propose that cell-surface CK 8 may be important in promoting invasion of breast cancer cells.

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**Characterization of the Binding Sites for Plasminogen and Tissue-type
Plasminogen Activator in Cytokeratin 8 and 18**

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Page-heading title - Binding of Plasminogen and t-PA to Cytokeratins

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SYNOPSIS - Cytokeratin 8 (CK 8) is an intermediate filament protein that penetrates to the external surfaces of breast cancer cells in culture and is released from cells in the form of soluble heteropolymers. CK8 binds plasminogen and tissue-type plasminogen activator (t-PA) and may accelerate the activation of plasminogen by t-PA on cancer cell surfaces. To characterize the binding of plasminogen and t-PA to CK8, we prepared three GST-fusion proteins. The first contained 174 amino acids from the C-terminus of CK8 (CK8f). The second was identical to the first except that the C-terminal lysine was mutated to glutamine (CK8f_{K483→Q}). The third contained 134 amino acids from the C-terminus of CK18 (CK18f). Immobilized CK8f and CK8f in solution bound plasminogen equivalently; the K_D was 0.5 μ M. Binding was completely inhibited by ϵ ACA. CK8f_{K483→Q} also bound plasminogen, albeit with decreased affinity (K_D of 1.5 μ M), demonstrating that the C-terminal lysine in CK8 is important but not essential for plasminogen binding. All three GST-CK fusion proteins bound t-PA; binding was not inhibited by ϵ ACA, indicating a role for the t-PA finger domain and not the kringle-2 domain. t-PA and plasminogen cross-competed for binding to CK8f; plasminogen did not inhibit t-PA-binding to CK18f. CK8f promoted the activation of plasminogen by t-PA, as did CK8f_{K483→Q}, although CK8f_{K483→Q} was less effective. CK18f did not promote plasminogen activation, suggesting that cofactor activity requires t-PA- and plasminogen-binding. In the intact cofactor complex, the enzyme (t-PA) and substrate (plasminogen) must be bound to separate cytokeratin monomers to form a tetramolecular complex since a single CK8 monomer cannot bind t-PA and plasminogen simultaneously.

INTRODUCTION

Cytokeratin 8 (CK8) is a member of the intermediate filament gene family, found in most simple epithelial cells and carcinomas [1]. CK8 typically forms heterodimers with CK18 and then polymerizes to form a component of the cytoskeleton [2]. The majority of cellular CK8 is present in an insoluble matrix within the cell; however, recent studies have shown that CK8 is present on the outer surfaces of intact, viable cancer cells [3,4]. Furthermore, CK8 can be recovered as part of a soluble heteropolymer released by cancer cells in culture [5,6]. The same complex is detected in the blood of cancer patients and has been referred to as Tissue Polypeptide Antigen [7]. Thus, CK 8 is available in the pericellular spaces and extracellular spaces at substantial levels *in vivo* in certain disease states.

We recently demonstrated that CK8, on the surfaces of cultured breast cancer cells, binds plasminogen and promotes the activation of plasminogen by tissue-type plasminogen activator (t-PA) [8]. We also purified CK8 from rat hepatocytes and demonstrated that the purified protein can bind plasminogen and t-PA and increase the rate of plasminogen activation [9]. Once activated, plasmin may promote the invasion of cancer cells through tissues by digesting glycoprotein components of the extracellular matrix [10] or by activating type IV collagenases [11]. Plasmin may also affect cellular phenotype by activating or inactivating growth factors, by modifying growth factor receptors, or by modifying adhesion receptors [12-15].

Many proteins serve as nonessential co-factors for t-PA-mediated plasminogen activation, including fibrin, histidine-rich glycoprotein, thrombospondin, type IV collagen, actin, and annexin II [16-21]. Cofactors may function exclusively by binding plasminogen

and converting the substrate into a more-open, readily activated conformation [22-25]. This form of cofactor activity is observed only with full-length [Glu¹]plasminogen, since [Lys⁷⁸]plasminogen is already in the open conformation. Furthermore, this form of cofactor activity can be mimicked by decreasing the Cl⁻ concentration or by lysine analogues such as ϵ -amino caproic acid (ϵ ACA), which also open the plasminogen conformation [25].

Fibrin is representative of a group of cofactors that increase the rate of activation of both [Glu¹]plasminogen, and [Lys⁷⁸]plasminogen by binding the plasminogen and t-PA to form a ternary complex [16,26]. Protein denaturation or aggregation may enhance the ability of proteins to function as cofactors for t-PA [26-28]. The reason for this may be at least two-fold. First, denatured proteins show increased affinity for t-PA. Second, denatured proteins are more susceptible to plasmin-degradation, which yields new C-terminal Lys residues that are required for plasminogen-binding. The structure of plasminogen includes five kringle domains, including at least three with potentially significant lysine-binding sites which mediate non-covalent interactions with cofactor proteins [22]. The structure of t-PA includes two kringle domains, a growth factor domain, and a finger domain; the kringle-2 domain and the finger domain have been implicated in non-covalent protein-binding interactions [29,30].

CK8 increases the rate of activation of both [Glu¹]plasminogen and [Lys⁷⁸]plasminogen by t-PA [9]. Thus, we hypothesized that CK8 functions as a cofactor by forming a ternary complex with plasminogen and t-PA. In support of this hypothesis, we demonstrated that purified CK8 binds t-PA, that was immobilized in microtiter plates [9]. Further studies to elucidate the interaction of plasminogen and t-PA with CK8 were precluded since purified

cytokeratins are highly insoluble. Thus, we have now prepared three glutathione-S-transferase (GST)-fusion proteins. The first contains 174 amino acids from the C-terminus of wild-type CK 8 (CK8f). The second is identical to the first except for the C-terminal lysine was mutated to glutamine (CK8f_{K483Q}). The third fusion protein contains 134 amino acids from the CK 18 C-terminus (CK18f). Our studies with these fusion proteins demonstrate that t-PA binds to both CK8 and CK18 by a mechanism which is apparently kringle-2 domain-independent. The interaction of plasminogen with CK8f is unique in that binding is not entirely dependent on the C-terminal lysine. The plasminogen and t-PA binding sites in CK 8 are non-identical but overlapping. Thus, the function of cytokeratin as a cofactor which promotes plasminogen activation must require the formation of a tetramolecular complex in which t-PA and plasminogen are bound to separate, aligned cytokeratin monomers.

MATERIALS AND METHODS

Materials

D-Valyl-L-leucyl-L-lysine-5-aminomethylcoumarin (VLK-AMC) was from Enzyme System Products (Livermore, CA, U.S.A.). Phenyl-prolyl-arginyl-chloromethylketone HCl (pPACK) was from Calbiochem (San Diego, CA, U.S.A.). Na¹²⁵I was from Amersham International (Arlington Heights, IL, U.S.A.). Iodo-Beads were from Pierce (Rockford, IL, U.S.A.). Bovine serum albumin (BSA), ϵ ACA, p-nitrophenyl-p'guanidino-benzoate (pNPGB), and lysozyme were from Sigma (St. Louis, MO, U.S.A.). Restriction enzymes were from New England Biolaboratories (Beverly, MA, U.S.A.).

Proteins and Antibodies

Recombinant human t-PA was provided by Genentech, Inc (San Francisco, CA, U.S.A.). Greater than 90% of the t-PA was in the single-chain form as determined by SDS-PAGE. [Glu¹]Plasminogen was purified from human plasma by the method of Deutsch and Mertz [31]. Final preparations contained a mixture of the two major glycoforms but were free of [Lys⁷⁸]plasminogen and plasmin as determined by SDS-PAGE. Miniplasminogen is a 38-kDa plasminogen derivative that lacks the first four kringle domains and thus does not bind lysine [32]. To prepare miniplasminogen, [Glu¹]plasminogen was digested with porcine elastase; the digestion products were then purified by chromatography on Lysine-Sepharose [33]. CNBr fragments of fibrinogen (Fg CNBr), which promote the activation of plasminogen by t-PA, were prepared as previously described [34]. The fusion protein, GST-receptor-associated protein (GST-RAP) was prepared for control experiments as previously described

[35]. The GST-RAP expression construct was a kind gift from Dr. Joachim Herz (Southwestern Medical Center, Dallas, TX, U.S.A.). Monoclonal antibody CY-90, which is specific for CK18, was from Sigma. Monoclonal antibody 1E8, which is specific for the C-terminus of CK8 was prepared and purified as previously described [8].

Preparation of GST-CK Fusion Proteins

Plasmids containing the full-length human CK8 cDNA (LK 442K8) and CK18 cDNA (LK442K18) were kindly provided by Dr. Robert Oshima (La Jolla, CA, U.S.A.). The CK8 cDNA was subcloned into pBluescript and then digested with *Bgl*III and *Eco*RI to yield a fragment (nucleotides 952-1724) encoding the C-terminal 174 amino acids of CK8. This fragment was ligated into pGEX-3X that was cut with *Bam*HI and *Eco*RI (Pharmacia) to yield the expression construct for CK8f. To generate CK8f_{K483Q}, the CK8 cDNA in pBluescript was treated with *Aat*II and *Kpn*I, removing a fragment that encoded 13 amino acids from the C-terminus of CK8 and the 3' untranslated region. Complementary oligonucleotides corresponding to the cDNA fragment that encodes the CK8 C-terminus, with the exception of a single nucleotide replacement (1481A→C) which resulted in the mutation from lysine to glutamine, were ligated back into *Aat* II/*Kpn*I-digested CK8-pBluescript. The *Eco*RI site was recreated by PCR. The final cDNA fragment was then excised with *Bgl*III and *Eco*RI and cloned into pGEX-3X. To generate CK18f, the CK18 cDNA was subcloned into pcDNA3. PCR was then used to amplify the sequence encoding 134 amino acids from the C-terminus, introducing an upstream *Bgl*III site. The PCR product was digested with *Bgl*III and *Eco*RI and ligated into pGEX-2T. All final constructs were verified by sequence

analysis and transformed into BL21 *E. coli* (Novagen). Expression was induced with 0.1 mM isopropyl- β -D-thiogalactopyranoside. The fusion proteins were purified from cell lysates by glutathione Sepharose-4B chromatography and characterized by SDS-PAGE and Western blot analysis with antibodies 1E8 and CY-90.

Binding of Plasminogen and t-PA to Immobilized GST-CK Fusion Proteins

CK8f, CK8f_{K483Q}, CK18f, and GST-RAP (2.5 μ g) were incubated in separate 96 well plates at 37° C for 1 h. The plates were then washed three times with Earle's balanced salts solution, supplemented with 10 mg/ml bovine serum albumin and 10 mM HEPES, pH 7.4 (EHB buffer), and blocked by incubation for 1 h at 37° C in the same buffer. Control wells were blocked with EHB without prior immobilization of fusion proteins. The amount of CK8f immobilized per well was 156 ± 17 ng (n=4).

Plasminogen and t-PA were radioiodinated with Iodobeads, according to the manufacturer's instructions. Specific activities ranged from 1-2 μ Ci/ μ g. Increasing concentrations of 125 I-plasminogen or 125 I-t-PA were incubated in wells with immobilized fusion proteins for 1 h at 25° C. Each incubation was conducted in the presence or absence of a 50-fold molar excess of non-radiolabeled ligand. In some experiments, 10 mM ϵ ACA was used instead of nonradiolabeled plasminogen to displace specific 125 I-plasminogen binding. ϵ ACA and nonradiolabeled plasminogen yielded equivalent results, as expected.

In radioligand displacement experiments, a constant concentration of 125 I-plasminogen (50 nM) or 125 I-t-PA (50 nM) was incubated with increasing concentrations of either nonradiolabeled protein in microtiter wells with immobilized fusion proteins. Incubations

were terminated by removing solutions and washing the wells three times with EHB. Bound radioligand was dissociated in 0.1 M NaOH, 1 % SDS and quantitated in a gamma counter. In experiments with ^{125}I -plasminogen or ^{125}I -t-PA, nonspecific binding was less than 15 % of total binding within the specified concentration ranges.

Analysis of GST-CK Fusion Protein Interactions in Solution

The binding of ^{125}I -plasminogen and ^{125}I -t-PA to GST-CK fusion proteins in solution was detected based on the ability of the CK-fusion proteins to inhibit binding of the radioligands to immobilized Fg-CNBr. Fg-CNBr was incubated in 96 well plates (50 $\mu\text{g}/\text{well}$), as described for the immobilization of CK-fusion proteins. The amount of immobilized Fg-CNBr was $2.2 \pm 0.3 \mu\text{g}/\text{well}$. The wells were then blocked with EHB. A constant concentration of ^{125}I -plasminogen or ^{125}I -t-PA (50 nM) was incubated in the Fg-CNBr-coated wells, in the presence of increasing concentrations of CK8f, CK 8f_{K483→Q}, or CK18f, for 1 h at 25° C. The wells were then washed. Radioactivity was recovered from the immobilized phase and quantitated in a gamma counter.

Continuous Plasminogen Activation Assays

CK8f, CK8f_{K483→Q}, and CK18f were immobilized in 96-well plates. Control wells did not contain GST-CK fusion protein but were blocked with EHB. Plasminogen (1 μM), t-PA (2 nM), and the plasmin specific fluorogenic substrate, VLK-AMC (0.5 mM), were added simultaneously to each well. VLK-AMC hydrolysis was detected by measuring fluorescence emission at 30 s intervals in a Cytofluor 2350 fluorescence plate reader (Millipore). The excitation wavelength was 380 nm and the emission wavelength was 480 nm (5 mm slit

widths). Relative fluorescence was plotted as a function of time. These graphs were converted using a first derivative function ($dRFU/dt$) to obtain plots of [plasmin] against time.

Discontinuous Plasminogen Activation Assays

Plasminogen (1 μ M) and t-PA (2 nM) were incubated with CK8f or GST-RAP (0.8 μ M) in EHB at 25° C for 80 min. At 20 min intervals, plasmin was quantitated by removing 50 μ L aliquots and incubating each with VLK-AMC (final concentration, 0.5 mM). Substrate hydrolysis was measured for 12 min in the Cytofluor. In this discontinuous assay, VLK-AMC is not present in the original plasminogen activation mixture. Thus, VLK-AMC and its hydrolysis products cannot affect the velocity of plasminogen activation, as has been reported for some plasmin-specific substrates [36].

SDS-PAGE Analysis of Plasminogen Activation

125 I-Plasminogen (1 μ M) and t-PA (2 nM) were incubated with CK8f (0.8 μ M) or BSA (150 μ M) in EBSS with 10 mM HEPES, pH 7.4, for 1 h at 25° C. At 15 min intervals, 50 μ L aliquots were removed from the incubation mixture and the reaction was terminated in these aliquots by the addition of 10 μ M pPACK and 0.1 mM pNPGB. The samples were then rapidly denatured in the presence of dithiothreitol (7 mg/ml) and subjected to SDS-PAGE. Dried gels were analyzed using a Phosphorimager. Plasminogen activation was detected by the conversion of the single-chain zymogen (92-kDa) into the active two-chain species (60- and 30-kDa).

FPLC of CK8f

CK8f was subjected to chromatography on prepacked Superose-12 columns. The flow rate was 0.4 ml/min. Fractions were collected at one min intervals. Elution of CK8f was detected by monitoring the absorbance at 280 nm. Individual elution fractions were also studied in plasminogen activation studies with VLK-AMC. To calibrate the FPLC, standard proteins were subjected to chromatography on the same column, including: soy bean trypsin inhibitor (M_r of 21,500, elution volume (V_e) of 14.1 ml), ovalbumin (M_r of 45,000, V_e of 12.9 ml), BSA (M_r of 66,000, V_e of 12.1 ml), and BSA dimer (M_r of 132,000, V_e of 10.9 ml).

RESULTS

Binding of Plasminogen and t-PA to GST-CK Fusion Proteins

Immobilized CK8f bound ^{125}I -plasminogen in a specific and saturable manner (Fig. 1). The K_D was $0.44 \pm 0.02 \mu\text{M}$ and the B_{MAX} was $1.6 \pm 0.1 \text{ pmol/well}$ ($n=3$). At saturation, 0.5 mol of plasminogen were bound per mol of immobilized CK8f monomer. Immobilized CK8f_{K483Q} also bound ^{125}I -plasminogen; however, the binding affinity was substantially decreased. Based on Scatchard transformation, the K_D was $1.5 \pm 0.4 \mu\text{M}$. ϵACA completely inhibited specific binding of plasminogen to CK8f and CK8f_{K483Q} (results not shown). CK18f did not bind ^{125}I -plasminogen. Thus, specific binding of plasminogen to CK8f and CK8f_{K483Q} was due to the CK 8 and not GST.

^{125}I -t-PA bound comparably to CK8f, CK8f_{K483Q}, and CK18f. The K_D values were $0.5 \pm 0.2 \mu\text{M}$, $0.6 \pm 0.3 \mu\text{M}$, and $0.8 \pm 0.2 \mu\text{M}$, respectively ($n=4$). The ability of CK8f_{K483Q} to bind t-PA without loss of affinity suggests that the C-terminal lysine residue in CK8 is not a component of the t-PA binding site. GST-RAP did not bind ^{125}I -t-PA, indicating that the t-PA binding site is contained within the cytokeratin-portion of the fusion protein.

Role of the CK8f C-terminal lysine in ^{125}I -t-PA-binding

The t-PA-binding studies with CK8f_{K483Q} addressed the role of the CK8 C-terminal lysine in t-PA-binding. To further probe for involvement of lysine-binding in the t-PA/CK8 interaction, t-PA was incubated with immobilized CK8f and CK8f_{K483Q} in the presence of 10 mM ϵACA . As shown in Fig. 2, ϵACA had no effect on the binding of t-PA to either fusion protein. Thus, the lysine-binding site in t-PA (kringle-2 domain) is not involved in the CK8

interaction. Since the C-terminal lysine is a major component of the plasminogen binding site in CK8f, the plasminogen and t-PA binding sites are not identical. PPACK-inactivated t-PA bound to immobilized CK8f with unchanged affinity, indicating that the t-PA active site is not required for this interaction (results not shown).

Binding of Plasminogen and t-PA to GST-CK Fusion Proteins in Solution

Fg-CNBr binds ^{125}I -plasminogen and ^{125}I -t-PA [34,37,38]. To study the binding of plasminogen and t-PA to GST-CK fusion proteins in solution, Fg-CNBr was immobilized in microtiter plates. Binding of ^{125}I -t-PA and ^{125}I -plasminogen to the fusion proteins was detected as a decrease in the binding of the radioligands to the immobilized phase. In the absence of fusion proteins, 10 ± 2 pmol of ^{125}I -plasminogen and 3 ± 1 pmol of ^{125}I -t-PA bound to the Fg-CNBr. As shown in Fig. 3, CK8f inhibited the binding of plasminogen to the Fg-CNBr. The IC_{50} was $0.6 \pm 0.1 \mu\text{M}$, in good agreement with the K_D determined for the binding of plasminogen to immobilized CK8f. CK8f_{K483Q} also inhibited the binding of ^{125}I -plasminogen to Fg-CNBr, confirming that this mutant retains plasminogen-binding activity. The IC_{50} was $1.9 \pm 0.3 \mu\text{M}$. CK18f did not inhibit the binding of plasminogen to Fg-CNBr.

All three fusion proteins inhibited the binding of t-PA to the Fg-CNBr, as expected. The IC_{50} values were $1.0 \pm 0.2 \mu\text{M}$, $0.9 \pm 0.1 \mu\text{M}$, and $1.2 \pm 0.2 \mu\text{M}$ for CK8f, CK8f_{K483Q}, and CK18f, respectively. Thus, binding of plasminogen and t-PA to the GST-CK fusion proteins was not dependent on the immobilization of the fusion proteins.

Relationship of the t-PA and Plasminogen Binding Sites in CK8f

Since the C-terminal lysine in CK8f is an important component of the plasminogen binding

site but is not involved in t-PA binding, we hypothesized that the plasminogen and t-PA binding sites are non-identical. To further explore the relationship between the plasminogen and t-PA binding sites in CK8f, competition experiments were performed using immobilized CK8f. Fig. 4 shows that nonradiolabeled plasminogen and t-PA both inhibited ^{125}I -plasminogen binding to CK8f. The IC_{50} values for unlabeled t-PA and plasminogen were $0.6 \pm 0.1 \mu\text{M}$ and $0.8 \pm 0.1 \mu\text{M}$, respectively ($n=4$). When the t-PA concentration exceeded $3.0 \mu\text{M}$, ^{125}I -plasminogen binding was essentially eliminated. Thus, plasminogen and t-PA binding to CK8f are mutually exclusive, even though the binding sites are not identical. To confirm this conclusion, the identical experiment was performed with ^{125}I -t-PA. Again, competition was observed with both plasminogen and t-PA; the K_i values were $0.7 \pm 0.1 \mu\text{M}$ and $0.7 \pm 0.1 \mu\text{M}$ for t-PA and plasminogen, respectively ($n=4$).

Since t-PA and plasminogen cross-competed for binding to CK8f, experiments were performed to confirm that plasminogen does not inhibit t-PA-binding to CK18. CK18f was immobilized in microtiter wells. As anticipated, nonradiolabeled t-PA inhibited the binding of ^{125}I -t-PA to CK18f; the K_i was $0.8 \pm 0.2 \mu\text{M}$. By contrast, plasminogen did not inhibit the binding of ^{125}I -t-PA to CK18f. These results confirm the non-identity of the binding sites for plasminogen and t-PA in the cytokeratins.

Plasminogen Activation in the Presence of Immobilized GST-CK Fusion Proteins

Continuous plasminogen activation experiments were performed in microtiter wells that were pre-coated with GST-CK fusion proteins. t-PA, plasminogen, and VLK-AMC were added simultaneously to the wells and fluorescence was monitored as a function of time. Fig. 5

shows that the rate of plasminogen activation was accelerated in wells that were pre-coated with CK8f or CK8f_{K483Q}. A very minimal effect was observed in some studies with CK18f. ϵ ACA completely neutralized the activities of immobilized CK8f or CK8f_{K483Q}, indicating an essential role for plasminogen-binding. The first-derivative plots in panel B show that the rates of plasminogen activation in wells pre-coated with CK8f or CK8f_{K483Q} maximized only after an initial 10-30 min lag phase. This lag phase probably represented the time required for t-PA and plasminogen to bind to the immobilized protein; however, during the lag phase, plasmin may have partially digested the immobilized cytokeratin, increasing its capacity for plasminogen binding. In five separate experiments, CK8f increased the rate of plasminogen activation by 10 ± 1 fold (compared with the rate measured in BSA-blocked wells); CK8f_{K483Q} increased the rate of plasminogen activation 6 ± 2 -fold. Based on our equilibrium binding studies, we estimated that 10% or less of the t-PA was CK8f- or CK8f_{K483Q}-associated in the plasminogen activation studies. Assuming that solution-phase t-PA does not activate CK8f-associated plasminogen at an accelerated rate, then the rate of plasminogen activation by CK8f-associated t-PA is actually increased more than 100-fold.

To confirm that plasminogen-binding to CK8f is required for accelerated activation, experiments were performed with miniplasminogen. This plasminogen derivative lacks four kringle domains and thus has little or no capacity to associate with most plasminogen-binding proteins [32]. None of the immobilized GST-CK-fusion proteins increased the rate of miniplasminogen activation by t-PA (results not shown).

Plasminogen activation in the presence of CK8f in solution

Plasminogen activation was accelerated by CK8f in solution ($1.0\ \mu\text{M}$), as determined in a discontinuous assay (VLK-AMC not present in the plasminogen activation solution). Fig. 6 shows a representative study in which plasminogen was activated by t-PA in the presence of CK8f and GST-RAP. In three separate experiments, the rate of plasminogen activation was accelerated an average of 8-fold by CK8f. Based on our binding studies, we estimated that about 50% of the t-PA was CK8f-associated in these solution-phase plasminogen activation experiments. Thus, the rate of plasminogen activation by CK8f-associated t-PA was probably increased by 15-20-fold; however, CK8f still may not have been as effective at promoting plasminogen activation, compared with immobilized CK8f (discussed below).

Fig. 7 shows an analysis of plasminogen activation based on the conversion of plasminogen into active two-chain plasmin. ^{125}I -plasminogen was used in this activation study so that the plasmin heavy chain (60-kDa) and light chain (30-kDa) could be detected in the presence of high concentrations of fusion protein and BSA. Within 60 min, conversion of plasminogen into two-chain plasmin was not apparent in the presence of $150\ \mu\text{M}$ BSA. When $0.8\ \mu\text{M}$ CK8f was included, significant amounts of plasmin heavy chain and light chain were generated. This study confirms the ability of CK8f to activate plasminogen without prior immobilization.

Analysis of CK8f self-association

Others have shown that GST-fusion proteins associate as noncovalent dimers due to an interaction between the GST subunits (48,49). It has also been suggested that denatured and aggregated proteins may preferentially stimulate plasminogen activation (30). Thus, we

subjected CK8f to FPLC in order to determine the state of association of the fusion protein. One major double-peak was observed; the peak-centers corresponded to molecular masses of 81-kDa and 167-kDa (Fig. 8). The peak at 81-kDa is consistent with the predicted mass of the CK8f dimer. The peak at 167-kDa suggests that some dimers associate to form tetramers. A small but rapidly eluting peak suggested that a minor percentage of the CK8f was in the form of aggregates. To demonstrate that the aggregates were not independently responsible for accelerating plasminogen activation, chromatography fractions were diluted 1:2 into a solution that contained plasminogen and t-PA; plasminogen activation was then studied using a discontinuous assay with VLK-AMC. As shown in Fig. 8, fractions which contained CK8f dimers and tetramers accelerated plasminogen activation. Thus, plasminogen activation is accelerated by CK8f in its un-aggregated form.

DISCUSSION

CK8 that is purified from rat liver accelerates the activation of plasminogen by t-PA [9]. Increased rates of activation are observed with [Glu¹]plasminogen and [Lys⁷⁸]plasminogen, suggesting that the mechanism involves binding of the enzyme (t-PA) and substrate (plasminogen) to the modifier (CK8). We demonstrated that t-PA binds to purified CK8 [9]; however, in order to maintain the CK8 in solution, it was necessary to expose the protein to denaturants, which may have revealed cryptic t-PA binding sites [36]. Furthermore, it was not possible to conduct experiments with purified CK8 in solution. Thus, in our previous studies [9], the purified CK8 was immobilized. This precluded detailed analysis of CK8-t-PA and CK-8-plasminogen interactions.

Antibody 1E8, which binds to the C-terminus of CK8, blocks plasminogen-binding to the cell surface and inhibits the activation of plasminogen by t-PA [8], thus identifying a potentially significant role for the small fraction of cellular CK 8 which is surface-exposed. To analyze the function of CK8 as a binding protein for plasminogen and t-PA, we expressed 174 amino acids from the C-terminus of CK8 as a GST-fusion protein. This fusion protein, CK8f, bound plasminogen without significant loss of affinity compared with intact CK8 [9]. The mutant form of CK8, CK8f_{K483Q}, also bound plasminogen, although with decreased affinity while CK18f did not bind plasminogen at all. The ability of CK8f_{K483Q} to bind plasminogen suggests that amino acids in CK8f, other than the C-terminal lysine, are involved in the interaction. Miles et al. [39] examined a series of peptides and demonstrated that C-terminal lysines are necessary for plasminogen-binding; however, the same

investigators demonstrated that the affinity of plasminogen for C-terminal lysine-containing peptides is influenced by adjacent amino acids. Although the amino acids in CK8f which support the C-terminal lysine in plasminogen-binding remain to be determined, the lysine, which is located 11 amino acids from the C-terminus is probably involved since plasminogen-binding to CK8f_{K483Q} was inhibited by ϵ ACA. Hortin et al. [40] demonstrated that a lysine which is 17 residues from the C-terminus of α_2 -antiplasmin plays an important role in plasminogen-binding as well. Interestingly, the proline residue which is immediately N-terminal to the C-terminal lysine in CK8 is conserved in other plasminogen binding proteins, including α_2 -antiplasmin and histidine-proline-rich glycoprotein [18,40].

All three of the GST-CK fusion proteins bound t-PA with similar affinity. The ability of CK18 to bind t-PA was previously unrecognized. Binding of t-PA to the cytokeratins was specific in that the control GST-fusion protein, GST-RAP, did not bind t-PA. The interaction of t-PA with the GST-CK fusion proteins was somewhat unique in that it was not inhibited by ϵ ACA. This property distinguishes the t-PA-cytokeratin interaction from previously reported interactions of t-PA with proteins such as actin [41], α -enolase [42], and amphoterin [43] and suggests that the t-PA finger domain, and not kringle-2, is involved. The t-PA-binding activity of CK8f_{K483Q} further supports the conclusion that the t-PA kringle-2 domain is not involved in cytokeratin-binding. Felez et al. [42] screened nine cell lines and showed that t-PA and plasminogen cross-compete for cell-surface binding sites in all nine. We do not know whether CK8 or CK18 are expressed on the surfaces of the cell lines studied by Felez et al. [42]; however, our data suggest that t-PA and plasminogen cross-compete for CK8 which is expressed on the surfaces of cultured cells. If CK18 is also

available at the cell surface, then this protein may mediate t-PA-binding which is not inhibited by plasminogen.

Multiple lines of evidence suggest that t-PA-binding to the cytokeratins alone does not promote its activity towards plasminogen; binding of plasminogen is required as well. First, ϵ ACA, which did not affect t-PA binding to any of the fusion proteins, completely neutralized the effects of the fusion proteins on plasminogen activation. Second, -miniplasminogen activation by t-PA was not accelerated by the fusion proteins. Finally, CK18f, which bound t-PA comparably to the CK8-based fusion proteins, did not promote plasminogen activation. The ability of CK8f_{K483Q} to accelerate the activation of plasminogen by t-PA provides further evidence for a C-terminal lysine-independent interaction between this fusion protein and plasminogen. Once plasmin is generated, the fusion proteins may become plasmin substrates; this reaction yields new C-terminal lysines and enhances the potential of the cofactor to bind plasminogen [22].

In studies with CK8f, t-PA and plasminogen competed for binding sites, indicating that a single CK8 monomer cannot bind enzyme (t-PA) and substrate (plasminogen) simultaneously. Instead, a tetramolecular plasminogen activation complex must form, including two separate, spatially aligned cytokeratin monomers. A similar complex was proposed as one explanation for the enhanced activation of plasminogen by t-PA in the presence of histidine-proline rich glycoprotein; however, this cofactor promoted plasminogen activation only when immobilized and not while in solution [18]. The ability of CK8f to function as a cofactor in solution is probably related to its native structure, which is a dimer or tetramer, as determined by FPLC. In the soluble cofactor, at least two C-termini are

available and our results suggest that these regions are appropriately aligned to promote plasminogen activation. Our results showing potentially greater cofactor activity with immobilized CK8f, compared with solution-phase CK8f, suggests that alignment of the C-termini may be improved by immobilization. Since CK18 binds t-PA, the plasminogen activation complex on the cell surface, or in heteropolymeric complexes released from cancer cells, probably includes a plasminogen-binding protein (CK8) associated with a t-PA-binding protein (CK8 or CK18). CK8 and CK18 form heteropolymers in parallel orientation and exact axial register [44]. Thus, the C-terminal regions of CK8 and CK18 are adjacent and aligned for plasminogen activation-cofactor activity.

The well-characterized urokinase-type plasminogen activator (u-PA) receptor, uPAR, typically binds uPA with high affinity (K_D of 0.1-1.0 nM), which is probably well-matched to the concentration of uPA in the pericellular environment [45]. Thus, cellular expression of 10^3 - 10^4 copies of uPAR at the cell surface is typically sufficient to generate cell surface-proteolytic activity. By contrast, the K_D for t-PA-binding to CK8 and CK18 is two-three orders of magnitude higher than the concentration of t-PA which we have previously shown generates substantial amounts of plasmin in MCF-7 cell cultures [8]. This result is best explained by the high-capacity of the CK8-related plasminogen/t-PA receptor system in MCF-7 cultures. We identified between one and two million copies of CK8 on each MCF-7 cell-surface [3]. Thus, despite a fractional saturation well under 1%, we estimate that in our previous studies [8], between 5,000 and 10,000 t-PA molecules were bound to each MCF-7 cell at equilibrium.

In conclusion, we have characterized the interaction of plasminogen with CK8,

showing for the first time that this interaction is novel in that it is not entirely dependent on the CK8 C-terminal lysine. We have also shown for the first time that CK18 binds t-PA, as well as CK8. This interaction was also unique compared with many previously reported t-PA-binding interactions in that it apparently did not involve the kringle-2 domain. Finally, we have shown that cytokeratins express plasminogen activator cofactor activity that is dependent on plasminogen-binding.

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Footnotes:

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Abbreviations used: CK8, cytokeratin 8; CK18, cytokeratin 18; t-PA, tissue-type plasminogen activator; ϵ ACA, ϵ -amino caproic acid; GST, glutathione-S-transferase; CK8f, fusion protein containing 174 amino acids from CK8 C-terminus; CK8_{K483Q}, CK8f with mutated C-terminus; CK18f, fusion protein containing 134 amino acids from CK18 C-terminus; VLK-AMC, D-Valyl-L-leucyl-L-lysine-5-aminomethylcoumarin; pPACK, Phenyl-prolyl-arginyl-chloromethylketone HCl; pNPGB, p-nitrophenyl-p'guanidino-benzoate; RAP, receptor-associated protein; Fg-CNBr, CNBr fragments of fibrinogen; BSA, bovine serum albumin.

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FIGURE LEGENDS

Fig. 1. Specific binding of ^{125}I -plasminogen and ^{125}I -t-PA to immobilized CK-fusion proteins. Increasing concentrations of ^{125}I -plasminogen or ^{125}I -t-PA were incubated in wells coated with CK8f (●), CK8f_{K483Q} (■), CK18f (▲), GST-RAP (◇), or BSA (◆). Each point represents the average of three replicate determinations ($\pm$ S.E.M.) in four separate experiments.

Fig. 2. Specific binding of ^{125}I -t-PA to immobilized CK-fusion proteins in the presence of ϵACA . A representative study showing specific binding of increasing concentrations of ^{125}I -t-PA (0.1 μM - 1.5 μM) to immobilized CK8f (□,) or CK8f_{K483Q} (○). Binding was also preformed in the presence of 10 mM ϵACA (closed symbols).

Fig. 3. Binding of ^{125}I -plasminogen and ^{125}I -t-PA to CK-fusion proteins in solution. ^{125}I -plasminogen or ^{125}I -t-PA (50 nM) was incubated with immobilized Fn-CNBr in the presence of increasing concentrations of CK8f (●), CK8f_{K483Q} (▲), or CK18f (■). Each point represents the average of three replicate determinations ($\pm$ S.E.M.) in three separate experiments.

Fig. 4. Competition between plasminogen and t-PA for binding to immobilized CK8f. ^{125}I -plasminogen (●) or ^{125}I -t-PA (○) (each at 50 nM) was incubated on immobilized CK8f (panels A and B) or CK18f (panel C) with increasing concentrations of unlabeled plasminogen or t-PA. Each point represents the average of three replicate determinations ($\pm$ S.E.M.) in three separate

experiments.

Fig. 5. Plasminogen activation in the presence of immobilized CK-fusion proteins.

Activation of plasminogen (1 μ M) by t-PA (2nM) was studied in wells with immobilized CK8f ($\square$), CK8f_{K483Q} ($\blacklozenge$), CK18f ($\triangle$), or BSA ($\bullet$). The same reactions were also performed in the presence of 10 mM ϵ ACA ($\circ$, $\blacksquare$, $\diamond$). Pg activation was detected by monitoring plasmin-specific substrate (VLK-AMC) hydrolysis for 60 min. Panel A) VLK-AMC hydrolysis. Panel B) dF/dt of plots shown in panel A, representing the amount of plasmin present as a function of time.

Fig. 6. Fluorescence analysis of plasminogen activation in the presence of soluble CK8f.

Plasminogen (1 μ M) and t-PA (2 nM) were incubated with CK8f (0.8 μ M) ($\blacksquare$) or GST-RAP (0.8 μ M) ($\blacklozenge$) in solution.. At 20 minute intervals, an aliquot of the incubation solution was removed and added to the plasmin specific substrate, VLK-AMC. Linear points indicate a constant amount of plasmin present in the sample.

Fig. 7. SDS/PAGE analysis of plasminogen activation in the presence of soluble CK8f.

Autoradiography showing the activation of 125 I-plasminogen (1 μ M) by t-PA (2nM) in the presence of CK8Kf (0.8 μ M), or BSA (10 mg/ml). At the times shown, an aliquot of the incubation mixture was removed and the reaction was terminated by the addition of pPACK and pNPGB. Samples were then subjected to SDS-PAGE under reducing conditions.

Fig. 8. FPLC of CK8f preparation. The CK8f (500 μ g) preparation was subjected to molecular exclusion chromatography on a superose 12 column. Panel A) The profile of protein elution was detected by continuous monitoring of absorbance at 280 nm. Panel B) The ability of eluted CK8f to activate plasminogen. The final amount of fluorescence generated after 60 minutes is shown for selected fractions.

Figure 1

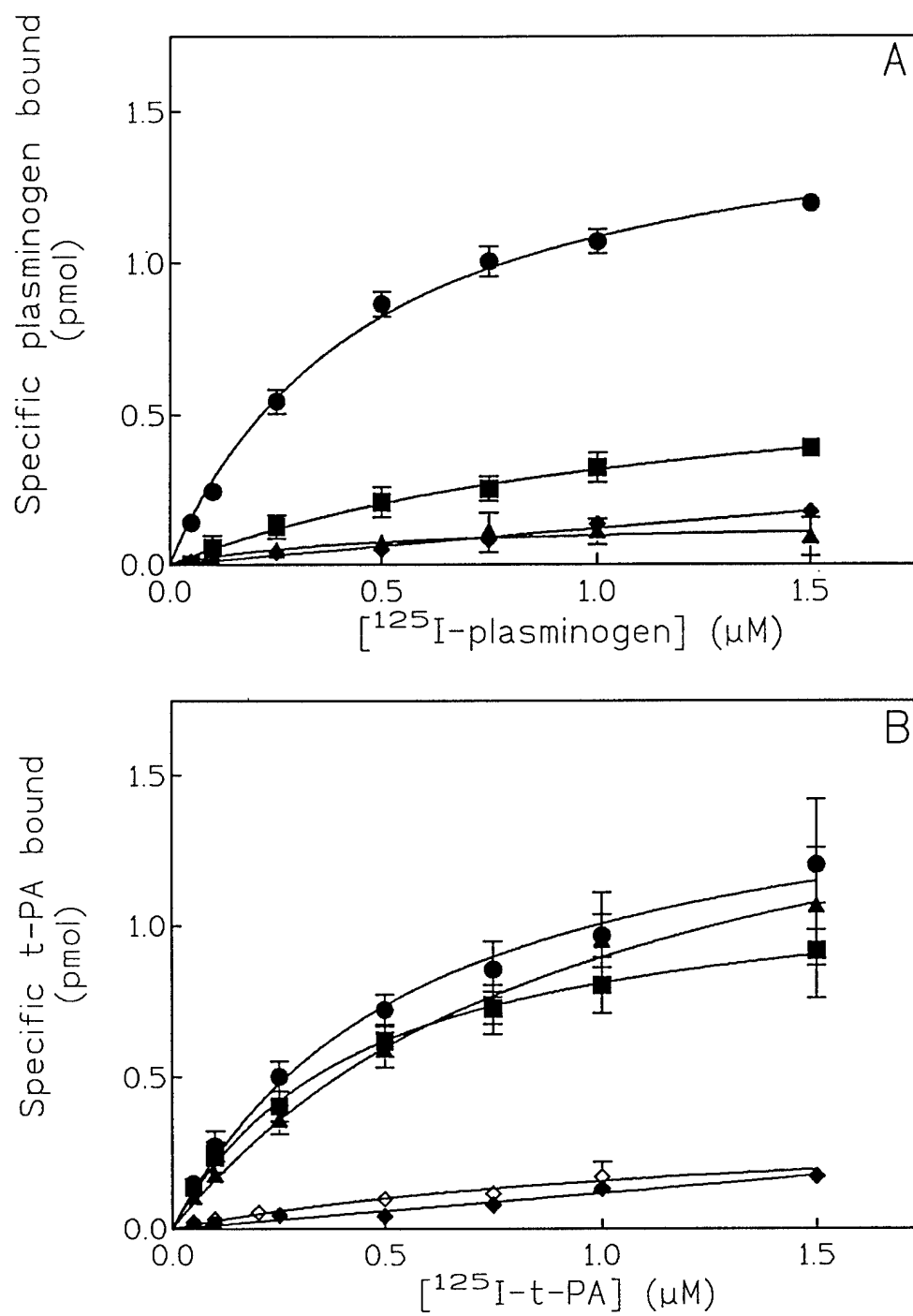


Figure 2

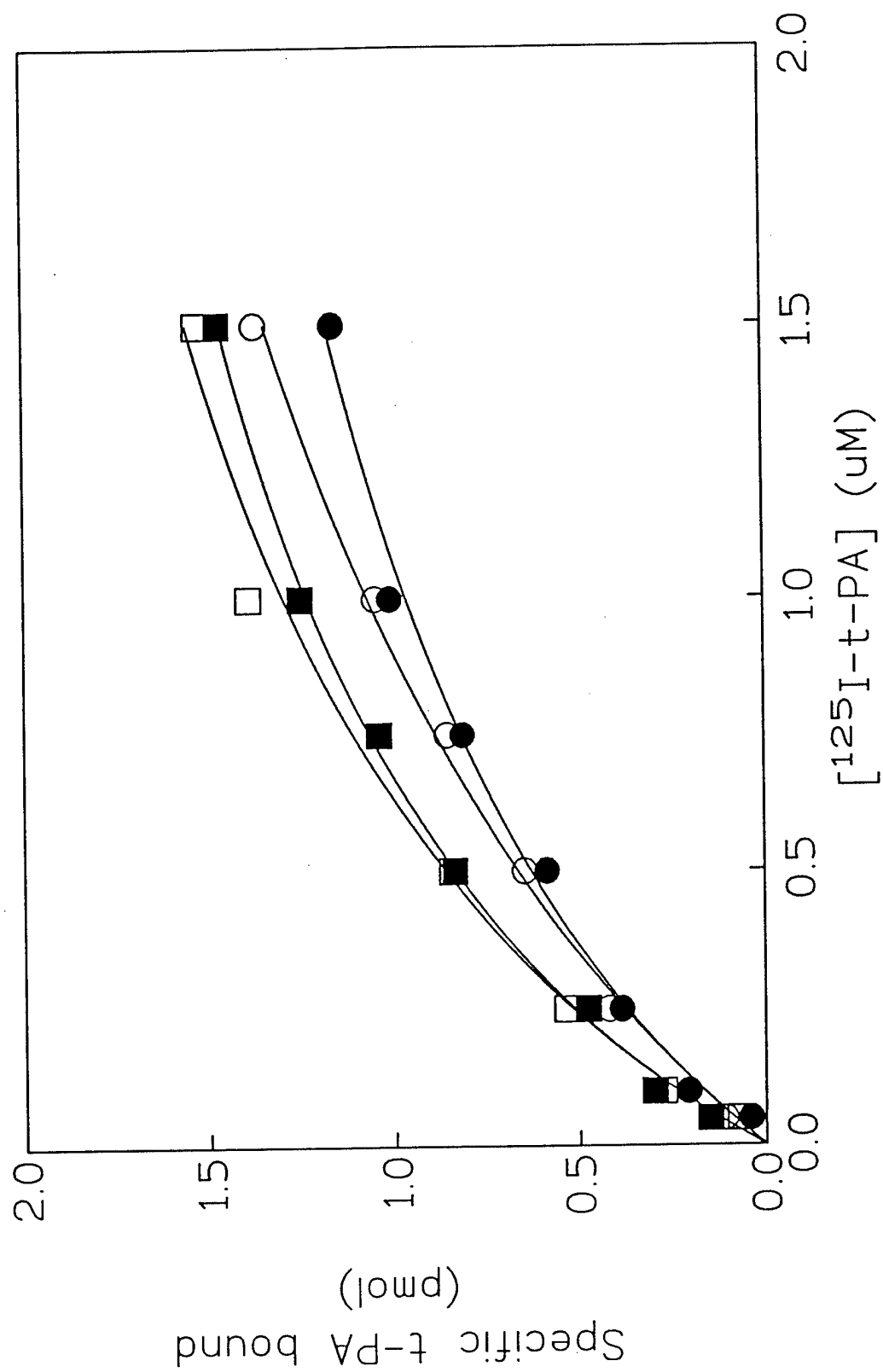


Figure 3

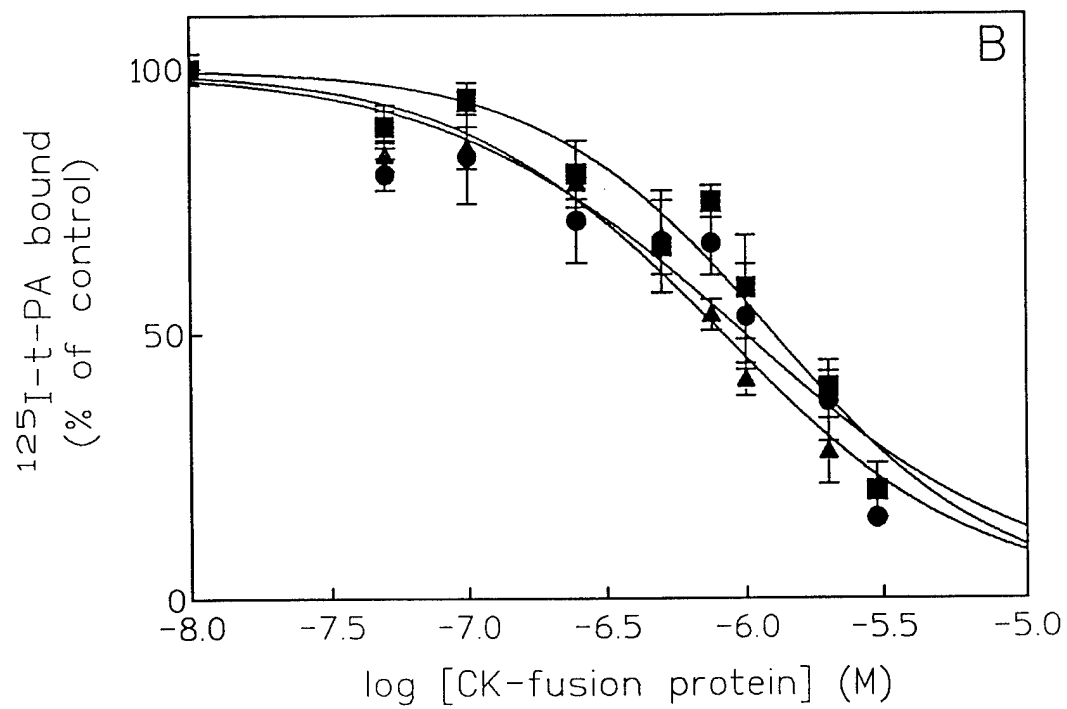
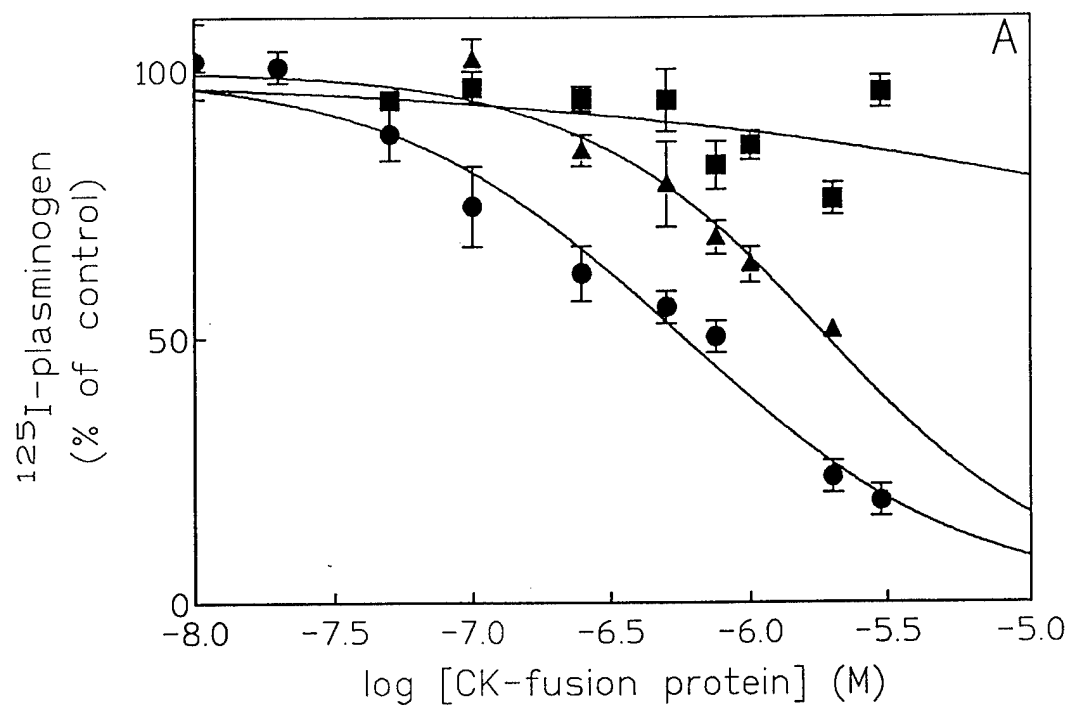


Figure 4

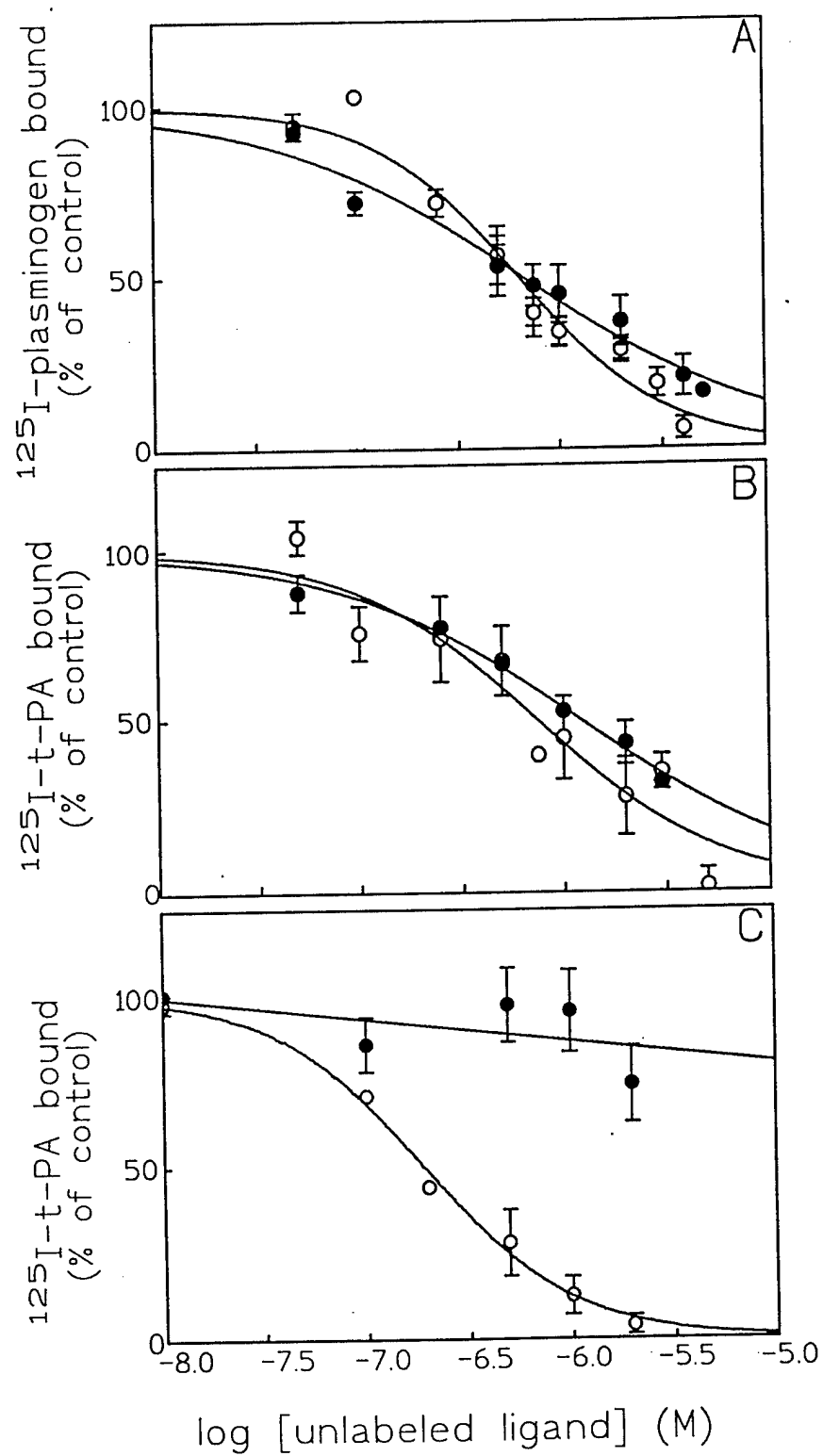


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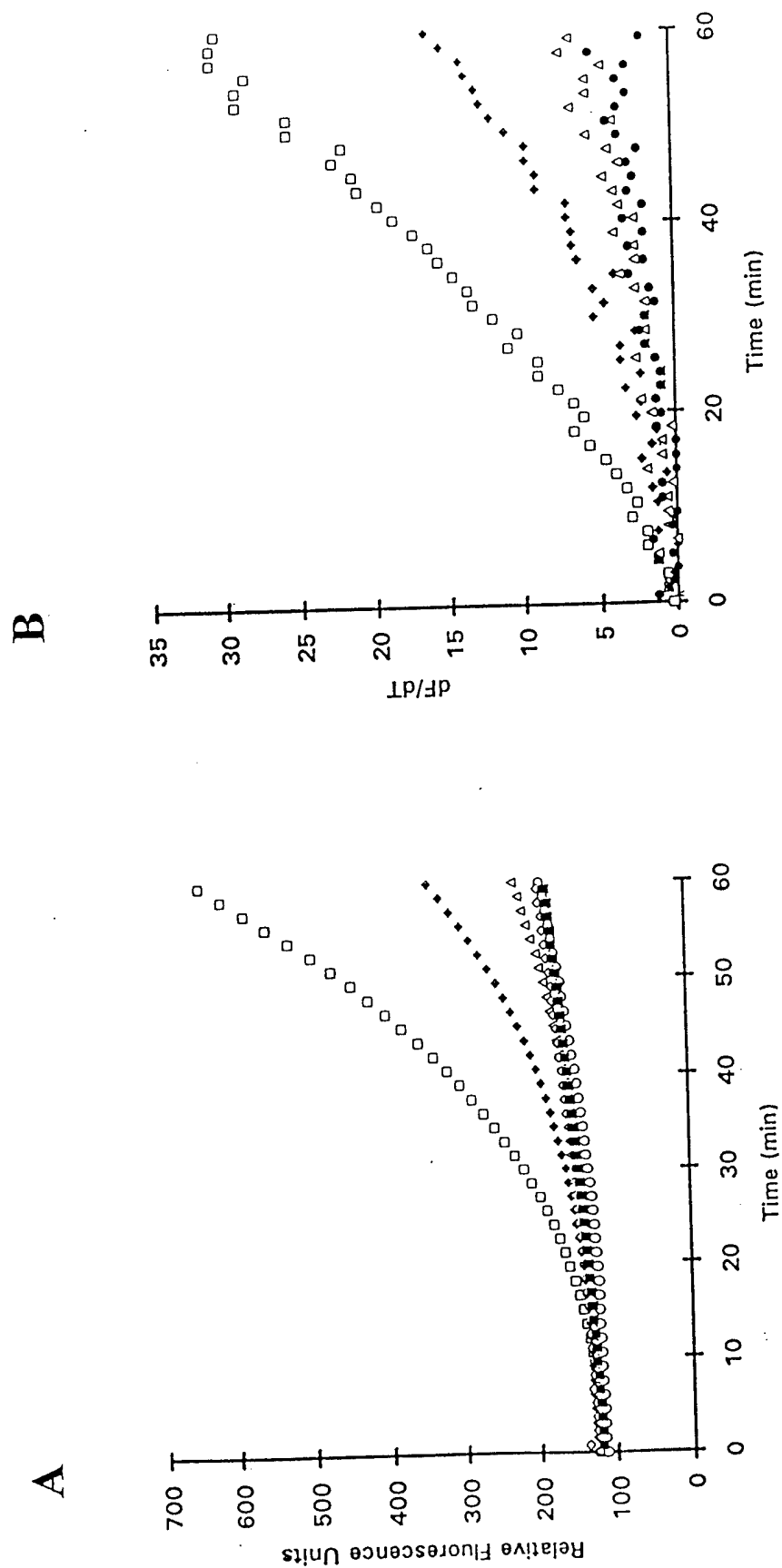


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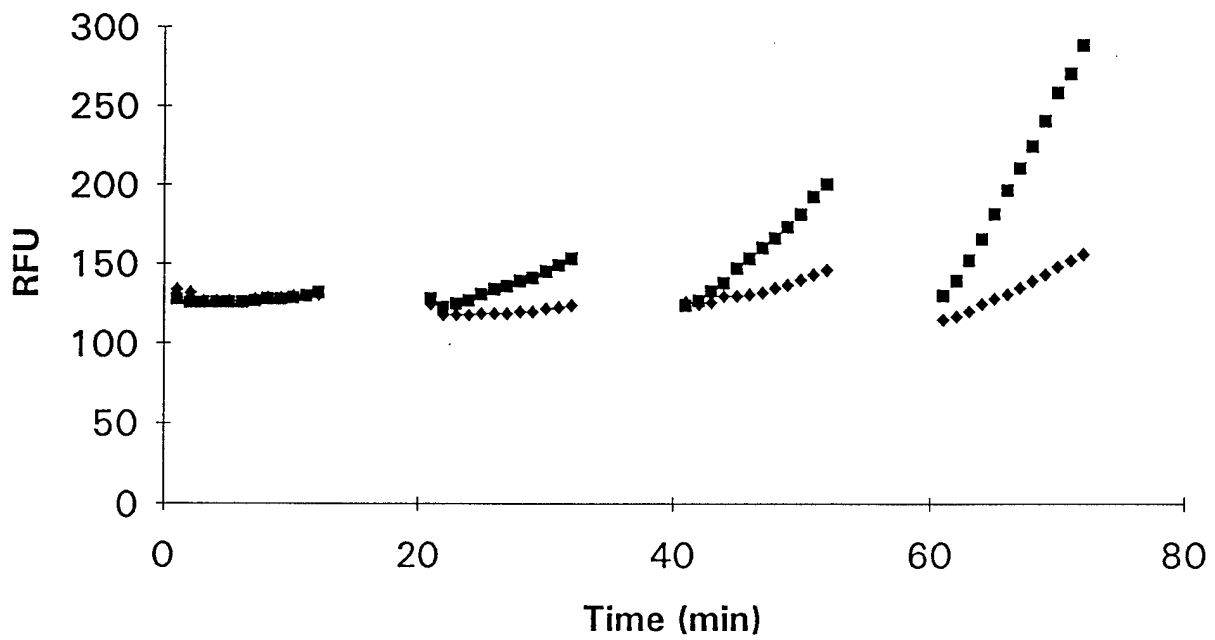


Figure 7

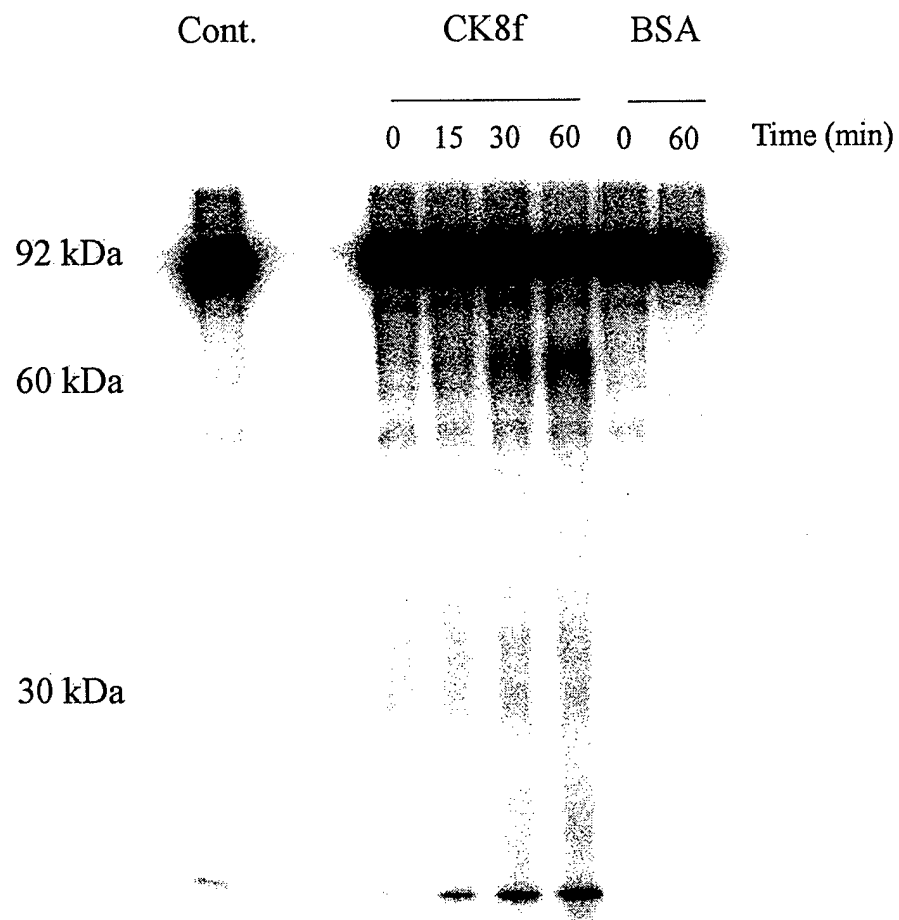


Figure 8

