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Sequential Binding of $\alpha_v \beta_3$ and ICAM-1 Determines Fibrin-Mediated Melanoma Capture and Stable Adhesion to CD11b/CD18 on Neutrophils

Pu Zhang,* Tugba Ozdemir,* Chin-Ying Chung,† Gavin P. Robertson,† and Cheng Dong* 

Fibrin (Fn) deposition defines several type 1 immune responses, including delayed-type hypersensitivity and autoimmunity in which polymorphonuclear leukocytes (PMNs) are involved. Fn monomer and fibrinogen are multivalent ligands for a variety of cell receptors during cell adhesion. These cell receptors provide critical linkage among thrombosis, inflammation, and cancer metastasis under venous flow conditions. However, the mechanisms of Fn-mediated interactions among immune cells and circulating tumor cells remain elusive. By using a cone-plate viscometer shear assay and dual-color flow cytometry, we demonstrated that soluble fibrinogen and Fn had different abilities to enhance heterotypic aggregation between PMNs and Lu1205 melanoma cells in a shear flow, regulated by thrombin binding. In addition, the involvement of integrin $\alpha_v \beta_3$, ICAM-1, and CD11b/CD18 (Mac-1) in fibrinogen-mediated melanoma–PMN aggregations was explored. Kinetic studies provided evidence that ICAM-1 mediated initial capture of melanoma cells by PMNs, whereas $\alpha_v \beta_3$ played a role in sustained adhesion of the two cell types at a shear rate of 62.5 s$^{-1}$. Quantitative analysis of the melanoma–PMN interactions conducted by a parallel-plate flow chamber assay further revealed that at a shear rate of 20 s$^{-1}$, $\alpha_v \beta_3$ had enough contact time to form bonds with Mac-1 via Fn, which could not otherwise occur at a shear rate higher than 62.5 s$^{-1}$. Our studies have captured a novel finding that leukocytes could be recruited to tumor cells via thrombin-mediated Fn formation within a tumor microenvironment, and $\alpha_v \beta_3$ and ICAM-1 may participate in multistep fibrinogen-mediated melanoma cell adhesion within the circulation. The Journal of Immunology, 2011, 186: 242–254.
intrinsinc binding properties between receptors and ligands on respective cell types. Therefore, without a proper affinity between receptors and ligands, cell–cell adhesion cannot occur in an ordered fashion. Most melanoma cells have been shown to lack necessary selectins and integrins that are responsible for the tethering/retaining of tumor cells to the endothelial wall within the circulation. Instead, melanoma cells do express high levels of ICAM-1 that can bind to β2 integrins such as LFA-1 (CD11a/CD18) and Mac-1. Recent studies have shown that ICAM-1–expressing melanoma cell could effectively adhere to PMNs in a very cooperative and sequential process, consisting of LFA-1–mediated initial capture and Mac-1–dependent firm adhesion (10).

In the presence of Fg or Fn, adhesion of melanoma cells to PMNs via fibrin(ogen) might follow a similar process mediated by bridging ICAM-1 (on melanoma) to fibrin(ogen) to β2 integrins (on PMNs), which is the main focus of this paper. Besides ICAM-1, melanoma cells express αvβ3, which can bind to Fg and Fn both under static and flow conditions (11–13). In melanoma cells, expression of αvβ3 is associated with metastatic phenotypes. Fg contains three potential αvβ3 binding sites at Aα95–98 (RGDF), Aα572–575 (RGDS), and γC400–411 (12, 13). Many cellular interactions with Fg and Fn occur via binding to one or two of these recognition sequences. Upon thrombin cleavage of fibrinopeptides A, Fg may expose more cryptic RGD sites that mediate stronger αvβ3 binding. The major ICAM-1 recognition site is located in γ117–133 of Fg (14). The leukocyte integrin Mac-1 is a high-affinity receptor for Fg on stimulated monocytes and PMNs, which has been implicated in many inflammatory responses. Mac-1 interaction site is localized within Fg D domain at a site corresponding to the γ-chain 190–202 and 377–395 (15).

The binding kinetics of melanoma cells and PMNs under hydrodynamic conditions has been recently investigated in the absence of fibrin(ogen) by using a cone-plate viscometer assay (16). The cell collision frequency, duration of cell–cell contact, and shear stresses acting on the cell could also be theoretically determined (9, 17). Because PMNs were shown to be involved in tumor cell extravasation and Fn levels were also shown an increase in cancer patients affected by plasma-contained thrombin (7, 18), we hypothesized in the current study that thrombin-regulated soluble Fn formation might mediate specific processes of melanoma–PMN binding by bridging the two cell types. In this paper, we have examined the binding of melanoma cells to Fn or Fg and its subsequent effects on melanoma–PMN adhesion. In addition, we have provided a quantitative comparison of relative roles in ICAM-1 and αvβ3-mediated melanoma–PMN interactions under various hydrodynamic shear conditions. We have found for the first time, to our best knowledge, that Fg and Fn-enhanced melanoma–PMN binding lies in a potential mechanism of ICAM-1–mediated initial capture followed by αvβ3–enhanced firm retention of melanoma adhesion to PMNs via fibrin(ogen). This enhancement of PMN–melanoma binding resulted in more melanoma being brought into close proximity of ECs, thereby representing a prelude of melanoma adhesion–led invasion and metastasis.

**Materials and Methods**

**Abs and reagents**

Mouse IgG anti-human mAbs against αvβ3 (anti-CD51/61, clone 23C6) and ICAM-1 (clone BBIG-I1) were purchased from R&D Systems (Minneapolis, MN). Mouse anti-human mAbs against LFA-1 (anti-CD11a) and Mac-1 (anti-CD11b) were purchased from Invitrogen (Carlsbad, CA). N-formyl-methionyl-leucyl-phenylalanine (fMLF), Fg (fraction I, type I from human plasma), Gly-Pro-Arg-Pro amide (GPRP), tetramethylrhodamine isothiocyanate isomer R (TRITC), chondroitinase AC II (*Arthrobacter aurescens*), and BSA were purchased from Sigma-Aldrich (St. Louis, MO). Fibronectin was obtained from VWR (West Chester, PA). Human serum albumin was purchased from Calbiochem (La Jolla, CA). Thrombin bovine (269N/µg) was purchased from MP Biomedicals (Solon, OH). LDS-751 was purchased from Invitrogen.

**Cell culture and preparation**

A375m, Lu1205, and WM35 (provided by Dr. Meenhard Herlyn, Wistar Institute, Philadelphia, PA) melanoma cells were grown in DMEM Nutrient Mixture F12 and RPMI 1640 (Life Technologies, Carlsbad, CA), respectively, supplemented with 10% FBS (BioSource International, Carlsbad, CA). Prior to each experiment, Lu1205 cells were detached with 0.05% trypsin/EDTA (Invitrogen) and washed twice with fresh medium. The cells were then suspended in fresh media and allowed to recover for 1 h while being rocked at a rate of 8 rpm at 37°C. In this way, ICAM-1 expression was not affected, whereas integrin αvβ3 could be regenerated after 1 h recovery (Fig. 1A, 1B). In some receptor-blocking experiments, Lu1205 cells were pretreated with respective functional blocking Ab (e.g., anti-αvβ3 [5 µg/ml], anti–hICAM-1 [5 µg/ml]), 30 min at 37°C, per set of assays. In selective experiments, to prevent CD44 binding to Fn, specific glycosaminoglycans from CD44 were removed by pretreating melanoma cells with 0.1 U/ml chondroitinase AC II [which catalyzed the cleavage of N-acetylatedhexosamine linkage in chondroitin sulfate and has been shown to significantly suppress binding of CD44-expressing cells to Fn (19)] for 1 h at 37°C.

PMN preparation was previously described (1). Following The Pennsylvania State University Institutional Review Board–approved protocols (number 19311), we collected fresh human blood from healthy adults by venipuncture. PMNs were isolated using a Ficoll–Hypaque (Histopaque, Sigma-Aldrich) density gradient as described by the manufacturer and kept at 4°C in Dulbecco’s PBS (DPBS) containing 0.1% human serum albumin for up to 4 h before an experiment. In selected experiments, PMNs were functionally blocked with anti–LFA-1 (5 µg/ml) and anti–Mac-1 (5 µg/ml).

Fibroblast-like cells that had been transfected to express human E-selectin and ICAM-1 (EI cells; kindly provided by Dr. Scott Simon, University of California Davis, Davis, CA) were maintained in culture as described elsewhere (1, 20). EI cells express ICAM-1 at a level comparable with IL-1β–stimulated HUVECs (21) and were used as a stable ICAM–1–expressing endothelial monolayer for some of the cell adhesion studies.

**Preparation of soluble fibrin solution**

Soluble Fn was made freshly in ion-free DPBS prior to each experiment. To produce soluble Fn monomers and prevent coagulation, thrombin cleavage of Fg was initiated in the presence of 4 mM GPRP-NH2 following...
a published protocol (19, 22). To probe the kinetics of Fn production, thrombin concentrations were varied while keeping a chosen dose from soluble Fg and GPRP. For example, to make 1 ml Fn solution, 120 μg Fg (25 mg/ml) and 168 μg GPRP (24 mW) were mixed with either 0.2 μl 2.7 μl 5.5 μl, or 207 μl thornbin (10 U/ml, 269,300 U/g) immediately preincubation at 37°C for 10 min. Then, a 2-fold concentrated Fn stock solution was subsequently mixed with cell suspension (containing tumor cells and/or PMNs) 1 h pre-experiment at a 1:1 ratio to reach a desired Fg, thornbin, GPRP, and cell concentrations.

SDS-PAGE for fibrinogen-digested products

To characterize thornbin catalyzed digestion of Fg (3 mg/ml), the reactions were run at room temperature and terminated at selected intervals by adding 2× SDS running buffer (0.2% bromophen blue, 4% SDS, 100 mM Tris [pH 6.8], 20% glycerol) and 2-ME. The samples were analyzed by SDS-PAGE on 12% gels. Control was prepared by adding SDS and 2-ME to Fg before thornbin and GPRP. Gels were stained with Coomassie blue and imaged accordingly.

Small interfering RNA targeting ICAM-1 and integrin αb3

A total of 100 pmol duplexed Stealth small interfering RNA (siRNA; Invi- trogen, Carlsbad, CA) was introduced into 1.0 × 107 1250Lui via nucleo- fication using an Ammax Nucleofector using Solution R/program K-17. Transfection efficiency was listed in Table II with 80–90% cell viability. Following siRNA introduction, cells were replated in culture dishes. siRNA sequences were: scrambled: 5′-AAUUCCCGAAGCCGACGAGCAGA-3′; ICAM-1: 5′-UUAAGAGGAGGUGCCGAGGGCUCG3′; integrin α3: 5′-UGAAGGAGCUGUUAGACUGGUGGA-3′; and integrin β3: 5′-AUAAGCAUCACAAUGGCGUAGGG-3′.

Binding of tumor cells or PMNs to immobilized fibrin or fibrinogen

Immobilized Fg surfaces were generated by absorbing Fg (from Willebrand factor-, plasminogen-, and fibronectin-free) solution at 2.5 mg/ml in DPBS containing 5 mM CaCl2 onto the substrate at 15-min polystyrene plate (BD Bionesciences, Franklin Lakes, NJ) overnight at 4°C. Similarly, immobilized Fn surfaces were generated by incubating the above-men- tioned Fg solution with thornbin (2 U/ml) for 2 h at 37°C (8). The non-specific binding sites were further blocked by incubating Fg- or Fn-coated surfaces with DPBS-1% BSA for 1 h at room temperature.

To assess circulating cells binding to immobilized fibrinogen, a par- allel-plate flow assay was adapted following previously published proto- cols (1), in which suspension of either tumor cells or PMNs (5 × 10^5/ml) in DMEM with 0.1% BSA was perfused over the Fn (or Fg)-coated surface of a parallel-plate flow chamber. The field of view was 800 cols (1), in which suspension of either tumor cells or PMNs (5–15 μm wide). DMEM alone was first perfused into the chamber to allow the melanoma-cell monolayer to reach equilibrium. fMLF-stimulated PMNs were then allowed to settle on the monolayer under a low shear rate of 10 s^-1 for 2 min before an onset of prescribed exper- imental shear rates (6.25 s^-1 or 20 s^-1). To simulate physiological conditions and assess melanoma adhesion to ECs assisted by PMN, suspension of fMLF-stimulated PMNs and melanoma cells at a ratio of 1:1 in the presence of Fg was perfused over an EC monolayer. To evaluate the capacity of PMNs to tether melanoma cells to ECs, melanoma adhesion efficiency was employed to quantify melanoma adhesion to the EI monolayer as a result of the collision with pretethered PMNs. If more than one melanoma cell adhered to a PMN, we counted it as multiple aggregates (e.g., two aggregates if two melanoma cells adhered to one PMN). Melanoma adhesion efficiency was expressed by the following ratio:

\[
\text{Number of melanoma cells arrested on the monolayer} \div \text{Number of melanoma collisions to PMNs}
\]

The adhesion efficiency was then classified based on the durations of melanoma arrests (>1 s, >3 s, and >5 s).

Cone-plate viscometer assay

To study binding of melanoma cells to PMNs both in suspension and under shear conditions, the flow assay was adapted using a cone-plate viscometer (RotoVisco 1, Haake, Hewington, NH) as previously described (16, 17, 24). This viscometer consists of a stationary plate and a 1°-free rotating cone, capable of generating linear velocity fields with a constant gradient (i.e., shear rate). So when cell suspension was subjected to a shear field within the instrument, the fast moving cells near the rotating cone collide with slowly moving cells near the plate (17). Cell–cell collision generated one bond initially. Once one bond formed, more bonds might form or existing bonds might dissociate when under shear for a longer time. The tensile force determined the dissociation rate of a doublet. To later quantify heterotypic cell aggregation, isolated PMNs and melanoma cells were stained with LDS-751 (red) and TRITC (orange), respectively, for 10 min at 37°C. Thereafter, PMNs were mixed with melanoma cells in DPBS containing Ca^{2+/Mg^{2+}} in the presence of 1 μM fMLF to reach a concen- tration of 5 × 10^5 cells/ml for each cell type (1:1). The cell suspension was allowed to equilibrate at 37°C for 2 min. Fibrinogen(ogen) was added, re- spectively, into the cell suspension 1 s preinietion of shear. Shear rates were varied from 62.5–200 s^{-1} for preset duration of time, ranging from 80–300 s. After shear applications, samples were fixed immediately with 1% formaldehyde.

Quantification of heterotypic cell aggregation

An ability of TRITC-labeled melanoma cells to form aggregates with LDS-751–labeled PMNs was determined by using the dual-color flow cytometry based on the cellular compositions, which were characterized by cells’ forward scatters, side scatters, and fluorescence profiles (Fig. 2) (16). Because the two cell types were labeled with different dyes, their aggre- gates would appear in the coordinates, which are integral multiples of singlet fluorescence values. A total of 5000 events were collected for each case. By applying this method, heterotypic aggregates comprised of a single tumor cell (T) with either one PMN (TP1), two PMNs (TP2), or more than three PMNs (TP3+) could be characterized. The extent of het- erotypic aggregation was defined as the percentage of bound tumor cells to PMNs in total amount of cells; % tumor cell in heterotypic aggregates = (TP1) + (TP2) + (TP3+)/TP1 + (TP2) + (TP3+).

Statistical analysis

Data were obtained from at least three independent experiments and expressed by the means. Statistical significance of difference between samples was determined by using Student t test or ANOVA. Turkey’s test was used for post hoc analysis for ANOVA. Probability values of p < 0.05 were chosen as statistical significance.

Results

Arrest of melanoma cells and PMNs on immobilized fibrin (ogen) under dynamic flow conditions

Melanoma cells express ICAM-1 and αb3 receptors for fibrin (ogen), for which levels correlate with their respective metastatic potentials (Table I) (11, 25). The way to prepare Lu1205 did not affect the expression of these receptors (Fig. 1A, 1B). To analyze how melanoma cells or PMNs bind to fibrin(ogen) ligands under different flow conditions, a parallel-plate flow system was used to immobilize ligands present on the substrate of the bottom plate. Perfusion of cell suspension over an immobilized Fn- or Fg-coated surface avoided some confounding factors and analysis for cell–cell and cell-soluble protein interactions in a three- dimensional flow field as shown in the following cone-plate assay (Fig. 2). When suspended in a binding buffer (DMEM + 0.1% BSA + HEPES), Lu1205 melanoma cells could bind to both immobilized Fn and Fg avidly at both low (62.5 s^{-1}) and high (200 s^{-1}) shear rates (Fig. 3A), although significantly more strongly to Fg than to Fn under low shear condition. Under both shear conditions tested,
Lu1205 melanoma cells directly arrested on immobilized Fn or Fg surface without an apparent rolling step. To show the specificity of interactions, Lu1205 cells were also perfused over a BSA-coated surface (as a control in Fig. 3A), which resulted in minimal surface-bound arrests, suggesting melanoma cell binding to fibrin(ogen) shown in Fig. 3A was protein specific.

To further illustrate cell-surface receptors are responsible for binding, Lu1205 were perfused over immobilized Fn at shear rate of 62.5 s$^{-1}$ in the presence of functional blocking mAbs, respectively, against ICAM-1, $\alpha_v\beta_3$, or IgG isotype control (5 mg/10^6 cells). As shown in Fig. 3B, the ability of Lu1205 cells to arrest on Fn under flow was only marginally affected by ICAM-1 blocking Ab, but much more effectively inhibited by anti-\(\alpha_v\beta_3\) mAb, which demonstrates that $\alpha_v\beta_3$ could be a more potent receptor than ICAM-1 on melanoma cells to support tumor cell adhesion to Fn and to make shear-resistant bonds.

PMNs were indicated to be capable of binding to either Fg- or Fn-coated surface under flow conditions (26, 27). To examine the effect of hydrodynamic shear force and chemoattractant stimulation on PMN binding to fibrin(ogen), nonstimulated or fMLF-stimulated (1 \mu M, 2 min) PMNs were perfused over an Fg- or Fn-coated surface in a parallel-plate flow chamber at a shear rate of 62.5 s$^{-1}$. As shown in Fig. 3C, nonstimulated PMNs had a higher affinity for Fn than for Fg during the 5 min perfusion time, whereas they failed to bind to the BSA-coated surface (as a control; data not shown). In comparison, fMLF, a potent activator for the high-affinity state of $\beta_2$ integrin, significantly enhanced PMN adhesion to both Fg and Fn (Fig. 3C). Like nonstimulated PMNs, activated PMNs bound to Fn with a higher affinity (220 PMN/mm²) than to Fg (90 PMN/mm²). Functional blocking Mac-1 Ab (5 mg/10^6 cells; for 30 min after being stimulated by fMLF) inhibited PMN binding to fibrin(ogen), which was in an agreement with previous studies (26). Taken together, results from Fig. 3C suggest that PMN adhesion to fibrin(ogen) is Mac-1 dependent.

Table 1. Flow cytometry analysis of ICAM-1 and $\alpha_v\beta_3$ expressions on WM35, A375m, and Lu1205 cells

<table>
<thead>
<tr>
<th>Receptor</th>
<th>WM35 (Low Metastatic)</th>
<th>A375m (Median Metastatic)</th>
<th>Lu1205 (Highly Metastatic)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control IgG</td>
<td>3.75 ± 0.03</td>
<td>3.75 ± 0.03</td>
<td>3.25 ± 0.49</td>
</tr>
<tr>
<td>ICAM-1</td>
<td>33.76 ± 0.25</td>
<td>106.76 ± 10.2</td>
<td>165.5 ± 12.8</td>
</tr>
<tr>
<td>$\alpha_v\beta_3$</td>
<td>26.22 ± 0.45</td>
<td>16.58 ± 0.36</td>
<td>45.5 ± 1.16</td>
</tr>
</tbody>
</table>

Values are geometric mean fluorescence intensities ± SEM (n > 3).
the reaction time would affect the kinetics of fibrinopeptide and Fn generation, and the amounts of generated Fn would have an impact on cell-cell interactions. To examine Fg-digested products, the components of Fg-thrombin reaction products were separated by SDS-PAGE to analyze the purity of Fn and mechanisms of thrombin catalysis. A total of 3 mg/ml Fn was cleaved by either 2 U/ml or 0.05 U/ml thrombin in the presence of GPRP for 10 min. The reactions were stopped by adding SDS and 2-ME. Proteins were resolved in 12% SDS-PAGE and stained with Coomassie blue (Fig. 4B). Fg α-, β-, and γ-chains were present on the gel as separate bands, and their molecular weights matched well with proposed data (29). After thrombin cleavage, smaller m.w. α- and β-chains were generated. In addition, the longer the time and the more thrombin, the more digested products were produced. Thrombin with a concentration of 2 U/ml could cleave all α- and β-chains within 10 min.

To understand the kinetics of melanoma–PMN aggregation, the percentage of melanoma cells recruited by PMNs was plotted as a function of time. In the absence of soluble Fg (0 mg/ml), the number of aggregates increased with time and maximized at 60 s, and then rapidly decreased (Fig. 5A). This behavior was similar to WM9 melanoma–PMN binding found previously (16), which might be partially due to a rapid decrease in the cell concentration, with time leading to a decrease in cell collision frequency, or due to time-dependent reduction of cell receptor affinity (30).

Adding Fg significantly elevated the percentage of heterotypic aggregation at shear rate of 62.5 s⁻¹ (Fig. 5A). The percentage of Lu1205 in aggregation still peaked at 60 s and descended thereafter, similar to the case in the absence of Fg. Initial capture and subsequent stable adhesion between the two cell types increased proportionally in the presence of Fg (Fig. 5A) compared with cases without Fg. This implies that soluble Fg largely increased effective forward rate for receptor–ligand binding while being capable of maintaining the tumor cell–PMN aggregation.

Adding Fn solution (made from 0.025 U/ml thrombin and 1.5 mg/ml Fg) altered the bifasic trend of pure Fg-mediated tumor cell–PMN heterotypic aggregation at 62.5 s⁻¹ (Fig. 5A). The presence of Fn allowed the binding to reach a steady state after the 60 s, increasing the percentage of aggregates from 48 to 57%, which sustained ≥5 min. In comparison, Fn solution made by 0.053 U/ml thrombin boosted the initial melanoma–PMN aggregation to the same level (63%) of the Fg case over a period of 60 s, followed by a plateau without an apparent dissociation over at least 5 min. However, catalyzing Fg–Fn transformation using 0.025 U/ml or 0.053 U/ml thrombin might result in only a partial conversion, which could make an analysis of Fn-mediated binding mechanism more difficult. Therefore, we also used 2 U/ml thrombin to make apparently more completed Fn solution (8). Indeed, results showed that Fn solution made from 2 U/ml thrombin changed initial capture rate of Lu1205 cells compared with that made from 0.053 U/ml thrombin. A total of 70% Lu1205 cells were recruited to aggregates within 60 s. However, the level of prolonged aggregation was not changed. Collectively, these results suggest that thrombin concentration in a tumor microenvironment could be very important, and conversion of Fg to Fn exposed some cryptic recognition sites that may stabilize the formed aggregates or other forms of coagulation.

Percentage of aggregation decreased with an increase in shear rates (Fig. 5B). For example, during the first 60 s, 1000 cell–cell collisions resulted in 38 captures at a low shear rate of 62.5 s⁻¹, whereas 1000 collisions only resulted in 8 captures at a higher shear rate of 200 s⁻¹. Fg was able to upregulate the extent of adhesion of PMNs to Lu1205 melanoma cells under high shear of 200 s⁻¹ to be comparable to that when Fg was absent under low

Binding rate of soluble proteins in solution to cell receptors follows an exponential-decay function of protein concentration (28). To approximately find the concentration-dependent Fg binding to melanoma cell and/or PMN receptors, the levels of melanoma–PMN aggregation mediated by soluble Fg with three arbitrary concentrations of 0.5, 1.5, and 3 mg/ml were compared (Fig. 4A). A total of 1.5 mg/ml Fg facilitated a significantly higher percentage of Lu1205–PMN heterotypic aggregation than 0.5 mg/ml Fg at 60 s. However, 3 mg/ml Fg did not further increase the extent of Lu1205–PMN aggregation compared with 1.5 mg/ml Fg concentration, suggesting a possible Fg saturation in mediating receptor–protein binding. Therefore, a 1.5 mg/ml concentration of Fg was chosen for probing Fg-mediated binding kinetics for the current study.

To understand potential mechanisms of Fn-mediated melanoma–PMN aggregation, Fn monomers were produced by reacting Fg, thrombin, and 4 mM GPRP. Conversion of Fg into Fn is initiated by thrombin-mediated cleavage in two NH2-terminal fibrinopeptides A and B (29). However, the concentrations of thrombin and the reaction time would affect the kinetics of fibrinopeptide and Fn generation, and the amounts of generated Fn would have an impact on cell–cell interactions. To examine Fg-digested products, the components of Fg-thrombin reaction products were separated by SDS-PAGE to analyze the purity of Fn and mechanisms of thrombin catalysis. A total of 3 mg/ml Fn was cleaved by either 2 U/ml or 0.05 U/ml thrombin in the presence of GPRP for 10 min. The reactions were stopped by adding SDS and 2-ME. Proteins were resolved in 12% SDS-PAGE and stained with Coomassie blue (Fig. 4B). Fg α-, β-, and γ-chains were present on the gel as separate bands, and their molecular weights matched well with proposed data (29). After thrombin cleavage, smaller m.w. α- and β-chains were generated. In addition, the longer the time and the more thrombin, the more digested products were produced. Thrombin with a concentration of 2 U/ml could cleave all α- and β-chains within 10 min.

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shear (62.5 s$^{-1}$) (Fig. 5A). According to the two-body collision theory, increasing shear rate may reduce capture efficiency due to an increase in fluid drag and tensile force in quickly rupturing transient bonds formation (9). Alternatively, increasing shear rate may also decrease the cell–cell encounter duration that limits the bond formation. Despite this transient feature of cell–cell aggregation at the shear rate of 200 s$^{-1}$, Fg was still able to slightly prolong the lifetime of aggregates. Fn solution made by 0.053 U/ml thrombin concentration shifted the peak binding from 60 s to 120 s at a higher shear rate of 200 s$^{-1}$. In general, Fn stabilized the transient process in tumor cell–PMN aggregation, given that it profoundly changed the time-dependent profile of fibrin(ogen)-mediated cell aggregation.

Compared with Lu1205 cells, WM35 cells, a low-metastatic melanoma cell line expressing lower amounts of receptors for fibrin(ogen) (Table I), failed to adhere efficiently to PMNs even in the presence of Fn at 200 s$^{-1}$ (Fig. 5C), which correlated melanoma–PMN binding abilities with tumor metastatic potentials. Taken together, results from Fig. 5A–C suggested that the recruitment of PMNs to melanoma cells was dependent on thrombin-mediated Fn production in a tumor microenvironment with respect to tumor metastatic phenotypes and circulatory shear rates.

**Relative roles of αβ3, ICAM-1, and Mac-1 in fibrin(ogen)-mediated binding**

Lu1205 cells were incubated with a panel of αβ3 functional blocking Abs before being subjected to shear experiments in the cone-plate viscometer to determine the role(s) of αβ3 in heterotypic tumor cell–PMN aggregation. αβ3 blocking did not affect the rate of Lu1205 binding to PMNs in the absence of fibrinogen (Fig. 6A), because αβ3 could not bind to β2 integrins on PMNs directly. Blocking αβ3 did not affect short-term binding between PMNs and Lu1205 melanoma cells in the presence of Fg (Fig. 6B). A total of 50% of Lu1205 cells were still able to bind to PMNs during the first 60 s, which could be due to the tethering via Fg between some unidentified receptors on the tumor cell and β2 integrins on PMNs, whereas the transient tethering quickly dissociated after 60 s, implying that Fg-dependent tethering did not sustain for longer time period during melanoma cell–PMN adhesion (Fig. 6B). Similarly, blocking αβ3 on melanoma cells had a marginal effect on initial Fn-mediated capture of Lu1205 cells to PMNs, whereas the percentage of aggregates was significantly reduced compared with nonblocking cases after 120 s (Fig. 6C). Therefore, interaction of αβ3 with Fn-bound Mac-1 sustained Lu1205–PMN binding. Interestingly, Fn apparently prolonged the duration of αβ3-dependent transient tethering from 60 s compared with the Fg cases up to 120 s (Fig. 6A, 6C).

If αβ3 mediates the sustained adhesion, a question remains as what receptors on melanoma cells would play roles in tethering tumor cells to PMNs in the presence of soluble fibrin(ogen) under hydrodynamic shear. Fn γ-chain contains the ICAM-1-binding sites with a lower affinity than that of RGD sites for integrins (14). Therefore, we rationalized that ICAM-1 and Fn interactions might have a high on-rate and off-rate in bridging melanoma cells to PMNs, which would reduce the traveling speed of melanoma cells and allow a longer contact duration between the two cell types. To investigate the role of ICAM-1 on Fn-mediated melanoma cell and PMN binding, ICAM-1 was blocked by treating Lu1205 cells with functional blocking Abs anti–ICAM-1 before the shear experiments. Fig. 6A shows that blocking ICAM-1 eliminated native tumor cell–PMN aggregation, given that ICAM-1 was the predominant receptor on Lu1205 melanoma cells that facilitated PMN–melanoma binding (16). The 10% aggregates at 60 s might represent nonspecific binding. Addition of Fg increased the extent of ICAM-1–blocked Lu1205 in heterotypic binding to PMNs by 15%, and these aggregates lasted >5 min under 62.5 s$^{-1}$ shear condition, suggesting a strong ability of αβ3 to bind to Fg (Fig. 6B). Conversion of Fg to Fn further modified the αβ3-dependent binding kinetics (Fig. 6C). Binding of αβ3 to Fn-bound Mac-1 slowly increased with time and reached a plateau at 120 s when 30% tumor cells were recruited to aggregates. These aggregates could sustain 5 min under shear without apparent disaggregation. However, blocking ICAM-1 reduced the rate of initial tethering of PMNs to Lu1205 cells in the presence of Fn by 60% (Fig. 6C, control versus anti–ICAM-1 case). This implies that the initial tethering (first 60 s binding postonset of shear) of Lu1205 cells to PMNs was due to ICAM-1 in terms of the high on-rate of ICAM-1–Fn binding.

LFA-1 has been shown to support the initial formation of melanoma–PMN aggregates (1). To distinguish LFA-1/ICAM-1-mediated initial tethering from potential Mac-1/Fn/ICAM-1-mediated events, we subsequently blocked LFA-1 on PMNs in ad-
PMNs was significantly smaller than that of scramble and buffer cases, and αβ3-mediated cell aggregation preceded very slowly and reached only 50% of the scramble and buffer cases at 5 min (Fig. 6E). These receptor knockdown results verified Ab blocking results, showing the relative roles of ICAM-1 and αβ3 in recruitment of Lu1205 cells to PMNs.

Mac-1 is involved in fibrin binding, whereas LFA-1 and CD44 are not

CD44 on carcinoma cells had an ability to bind to soluble Fn under flow conditions (8). Lu1205 melanoma cells express standard form of CD44 (CD44s; data not shown). Biochemical studies revealed that CD44s-fibrin(ogen) interaction was dependent on N-linked glycans that had a high affinity for Fn-β-chain, which was distinct from Mac-1, ICAM-1, and αβ3 recognition sites on Fn (19, 31).

To test whether other receptors, including CD44s, contribute to Fn-mediated PMN–Lu1205 heterotypic aggregation, ICAM-1 and αβ3 on Lu1205 cells were simultaneously blocked before shear experiments. Fig. 7A shows during 5 min shear, αβ3 supported 44% adhesion, ICAM-1 mediated 38% adhesion, whereas receptors other than these two supported 17% adhesion, indicating CD44s might not play as much roles as αβ3 and ICAM-1 in Fn-mediated PMN–Lu1205 melanoma cell heterotypic aggregation.

Pretreatment of PMNs with monoclonal anti-CD11b Ab inhibited the rate of their adhesion to Lu1205 cells via Fg by 50%, whereas the same Ab did not significantly affect the rate of their adhesion without Fg and slightly reduced longer term binding by 35% (Fig. 7B). This implied that Mac-1 participated in Fg- and Fn-mediated initial tether of PMNs to Lu1205, but only involved in sustained phase of native binding between PMN and Lu1205.

Interestingly, at 60 s, when Mac-1 was blocked, Fg seemed to inhibit LFA-1 binding (anti–Mac-1 with 1.5 mg/ml Fg versus anti–Mac-1 without Fg case). This may result from the occupancy of free binding sites on ICAM-1 by Fg.

To further demonstrate the roles of ICAM-1 and αβ3 in Fn binding, while ruling out the role of CD44, adhesive phenotypes among several melanoma cells with different metastatic potential were compared. This included Lu1205 cells expressing ICAM-1 and αβ3, A375 cells expressing high ICAM-1 (low αβ3) and WM35 cells expressing high αβ3 (low ICAM-1) (Table I). Before shear experiments, these cells were pretreated with chondroitinase AC II, which has been suggested to cleave binding motifs, like chondroitin sulfate and dermatan sulfate, on CD44 responsible for binding to Fn (19). Consistent with Ab blocking and siRNA knockout assays, the kinetics of WM35 binding mainly reflected that of αβ3, whereas A375m binding was primarily contributed by ICAM-1 and reiterated the kinetics of ICAM-1 binding (Fig. 7C). Their adhesive phenotypes did not seem to be affected by enzymatic treatment targeting CD44.

Fibrin(ogen) alters the mechanics of receptor-mediated melanoma cell adhesion to PMN and PMN-facilitated melanoma adhesion to ECs

To further elucidate the relative roles of αβ3, ICAM-1, and Mac-1 in fibrin(ogen)-mediated binding, direct video-microscopy observation of PMN–Lu1205 adhesion was obtained using a parallel-plate flow chamber assay in which a confluent Lu1205 cell monolayer served as a substrate of the flow chamber and PMNs were perfused over Lu1205 cells under two shear rates of 62.5 s⁻¹ and 20 s⁻¹, respectively. The kinetics of PMN binding to immobilized Lu1205 cells assayed by a parallel-plate flow chamber was not identical to the binding kinetics characterized in cone-plate viscometer shear assays in which both PMNs and tumor cells were in suspension. This is because cone-plate assay data reflected a...
statistical snapshot of the aggregate formation at a chosen time point, whereas a parallel-plate assay provided a direct quantification in a real-time individual PMN–Lu1205 aggregation formation. For example, Fig. 8A clearly showed that Fg only enhanced the longer-period binding (i.e., sustained adhesion) between PMNs and Lu1205 melanoma cells (statistically significant for length of stop >3 s), whereas Fn significantly enhanced both shorter- (i.e., initial tethered adhesion) and longer-period binding, which corroborated what we found in Fig. 8A when both cell types were in suspension under shear. In addition, in the presence of Fn, functional blocking of αβ3 on tumor cells significantly reduced firm adhesion (longer period >3 s) of PMNs to Lu1205 cells, whereas blocking ICAM-1 on tumor cells only reduced initial capture ability (significant for time <3 s) of Lu1205 cells under 62.5 s⁻¹ (Fig. 8B). This is again consistent with results from the cone-plate shear assay (Fig. 6C). Blocking ICAM-1 on Lu1205 cells did not significantly affect longer-period tumor cell binding to PMNs, suggesting it was the αβ3 that supported the firm adhesion in the presence of Fn. αβ3 on tumor cells was also shown to be sufficient in mediating optimal PMN–Lu1205 binding under very-low shear (20 s⁻¹) which allows a longer contact time between PMN–Lu1205 (Fig. 8C). In contrast to Lu1205, non-metastatic WM35 melanoma cells failed to support appreciable PMN adhesion even in the presence of Fn (Fig. 8D), demonstrating the metastatic tumor specificity.

Table II. Transfection efficiency

<table>
<thead>
<tr>
<th>Treatment</th>
<th>αβ3</th>
<th>ICAM-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buffer</td>
<td>13</td>
<td>30.51</td>
</tr>
<tr>
<td>Scramble</td>
<td>12.14</td>
<td>40.32</td>
</tr>
<tr>
<td>siRNA</td>
<td>3.11</td>
<td>15</td>
</tr>
<tr>
<td>Knockout efficiency*</td>
<td>77%</td>
<td>62%</td>
</tr>
</tbody>
</table>

*Knockout efficiency is defined as the ratio of siRNA fluorescence intensity to scramble fluorescence intensity.

Fibrinogen mediates melanoma–PMN aggregation, which may increase melanoma tethering to the endothelial wall and subsequently facilitate melanoma cell extravasation from the circulation (32). The mechanisms of bringing melanoma into close proximity to the endothelial cells by pretethered PMNs were studied in parallel plate flow assays with EI cells as a monolayer. In these experiments, it was observed that most of the melanoma cell binding to the EI under flow was enhanced by tethered PMNs. To normalize the resulting melanoma adhesion with respect to frequency of PMN–melanoma collision, a parameter, adhesion efficiency, was adopted (Materials and Methods, Fig. 8E). The time lengths of melanoma arrest on EI cells varied and were categorized to >1 s, >3 s, and >5 s. Fn affected melanoma adhesion to EI cells via tethered PMN more than Fg did (Fig. 8E). The 1 s short-term melanoma–PMN tethering on EI cells was mediated by ICAM-1 on the melanoma (less by αβ3), αβ3 maintained the bonds between PMN and melanoma, thereby setting melanoma on EI monolayer (Fig. 8F). These results indicate that thrombin-mediated Fg conversion to Fn plays influential roles in melanoma–PMN–EC adhesion, mechanistically via the receptors of ICAM-1 and αβ3 on melanoma.

In summary, our studies showed that fibrinogen could enhance the binding between PMNs and melanoma cells under shear conditions; ICAM-1 and αβ3 contributed to this process. Under hydrodynamic conditions, ICAM-1/Fn/Mac-1 and ICAM-1/LFA-1 bonds promoted effective cell–cell tethering and prolonged initial cell–cell contact duration, whereas αβ3/Fn/Mac-1 bonds enhanced cell–cell sustained adhesion, demonstrating cooperative roles of ICAM-1 and αβ3 in tumor cell–PMN adhesion in the presence of Fn (Fig. 9).

Discussion

In the current study, we have demonstrated that: 1) melanoma cells and PMNs can attach to immobilized Fg and Fn under venous flow conditions. αβ3 on Lu1205 melanoma cells and Mac-1 on PMNs are the primary receptors for binding to immobilized Fg and Fn; 2)
soluble Fg and Fn can enhance the heteroaggregation between melanoma cells and PMNs as the bridging molecules, although the kinetics of Fn-mediated binding is different from that of Fg; and 3) αvβ3 and ICAM-1 cooperate to mediate PMN and melanoma cell binding in the presence of soluble Fg or Fn under flow conditions, where ICAM-1 mediates initial tethering, whereas αvβ3 contributes to firm adhesion (Fig. 9).

**FIGURE 7.** Receptors on Lu1205 cells other than ICAM-1 and αvβ3 played marginal roles in Lu1205 and PMN heterotypic aggregation. A, The effect of ICAM-1 and CD51/61 blocking on Lu1205 and PMN heterotypic aggregation in the presence of Fn. Fibrin solution was made from 0.053 U/ml thrombin, 1.5 mg/ml Fg, and 4 mM GPRP. Values are means ± SEM from three independent experiments. B, The effect of Mac-1 blocking on Lu1205 and PMN heterotypic aggregation in the presence or absence of Fg. Values are means ± SEM (n > 3). C, The abilities of melanoma cells with different metastatic potentials and different receptor expressions to bind to PMNs in the presence of Fg. Lu1205 expresses high levels of ICAM-1 and αvβ3, A375m expresses median levels of ICAM-1 and low levels of αvβ3, and WM35 expresses median levels of αvβ3 and low levels of ICAM-1. Cells were pretreated with 1 U/ml chondroitinase AC II for 60 min at 37°C to remove terminal chondroitin sulfate and dermatan sulfate residues (on CD44). Values are means ± SEM (n > 3).

Soluble fibrin or fibrinogen, as a dimeric molecule, supports both initial capture and stable adhesion of melanoma cells to neutrophils under flow conditions

Tumor cells and PMNs in a cone-plate viscometer are subject to a uniform shear field, resulting in mutual collisions (9, 17). This millisecond scale of shear-dependent encounter has been shown to be able to mediate receptor–ligand bond formation between melanoma cells and PMNs in the absence of fibrinogen (16). Increasing shear force opposes bond formation by decreasing the cell contact duration but by increasing the cell–cell contact area. If the ensemble strength of receptor–ligand bonds outweigh tensile force, the heterotypic tumor cell–PMN aggregates form; otherwise, the aggregates dissociate. We now have shown that Fn mainly enhances the initial tethering of melanoma cells to PMNs, whereas Fn profoundly changes the kinetics of cell–cell binding, stabilizing melanoma–PMN doublets for several minutes. Results from Fig. 5A show that the extent of aggregation was increased with an increasing amount of Fg. However, this trend would be reversed after the concentration of soluble Fg reaches a certain level, because high amounts of free ligands tend to saturate counterreceptors on mutual cell types instead of bridging two cell receptors.

Tumor cell-mediated activation of coagulation cascade is a key factor for hematogenous metastasis. In this process, Fn plays various roles. Fn has also been shown to support migration of different cell types, including monocytes and fibroblasts. Its proteolytic products are chemotactic and angiogenic reagents. In addition, Fn is related to tumor stroma formation and invasion. Because thrombin generation is a determinant for Fn formation, it is interesting to see how thrombin affects tumor cell adhesion. ELISA results have shown that thrombin in plasma was increased when Lu1205 and A2058 melanoma cells were cultured or cocultured with HUVECs (data not shown). Thrombin enhances tumor cell adhesion to platelets and facilitated tumor cell metastasis in vivo (33). Thrombin may also promote tumor cell metastasis through an Fg-independent mechanism (7). The possible effect of thrombin on Fg can be described using a Michaelis-Menten scheme in which Fg binds to thrombin with certain rates and affinities (34). The rate of conversion of Fg to Fn is dependent on the concentration of thrombin. To understand the potential role of thrombin on conversion of Fg to Fn, we separated Fg-digested products with SDS-PAGE. Most of α- and β-chains were cleaved by thrombin to produce lower m.w. products. This demonstrated the functionality of thrombin and purity of Fn produced by 2 U/ml thrombin. Thrombin concentration of 2 U/ml was assumed to convert all the 1.5 mg/ml Fg to Fn within a 10-min incubation time period (8). To probe the sensitivity of cell adhesion to Fn concentration, we have varied the concentrations of thrombin for Fn generation. We tried a range of thrombin concentrations, varying from 0.0265 U/ml to 2 U/ml. Results have shown that Fn solution made from 0.053 U/ml thrombin significantly enhanced αvβ3-mediated firm adhesion between melanoma cells and PMNs, suggesting that cryptic αvβ3 binding sites are exposed by thrombin catalysis. When thrombin level was further increased to 2 U/ml from 0.053 U/ml, only the initial tethering phase was affected. This could imply that more ICAM-1 binding sites were available when melanoma cells were subject to higher concentration of thrombin. Therefore, we speculate that αvβ3 binding sites could be first exposed upon conversion of Fg to Fn, whereas it may require higher dose of thrombin to make ICAM-1 binding sites accessible. This hypothesis needs further biochemical analysis for proof. The fact that Fn has a higher affinity than Fg for receptors on melanoma cells agrees with the results from other cell types in which CD44 on carcinoma cells had a higher affinity for Fn than Fg (8, 9, 31). Thrombin may have
a potential effect on β2 integrin expression on PMNs. Therefore, the residual thrombin in our Fn solution may itself affect PMN–melanoma cell aggregation. However, it should be noted that all PMNs used in the current studies were prestimulated with fMLF, which boosted the Mac-1 expression to maximal levels when we conducted cone-plate and parallel plate assays (35). In this way, we can preclude the possibility that the observed Fn-mediated aggregation was the pseudoimage of thrombin-stimulated PMN–melanoma binding.

The concept of Fn-mediated melanoma cell and PMN aggregation under flow conditions is intriguing. Several earlier studies demonstrated that Fn might mediate platelet–tumor cell adhesion (3, 5). These platelet–tumor cell microemboli may tether tumor cells to the endothelial wall, thereby contributing to tumor metastasis. Other similar evidence of Fn-mediated cell–cell interaction came from the studies of leukocyte adhesion to EC, where Mac-1 on PMNs and ICAM-1 on the ECs may be the respective receptors for Fg (6, 25). To our best knowledge, the current study

FIGURE 8. Relative contributions of αvβ3 and ICAM-1 to fibrin(ogen)-mediated PMN–melanoma–EC interaction under flow in parallel plate. A–D, The number of PMNs contacting with Lu1205 or WM35 cells for >1 s (initial tethering), 3 s (transient adhesion), and 10 s (long-term adhesion): fibrin(ogen) enhanced PMN and melanoma cell interaction (A). Data are means ± SEM (n = 3). *p < 0.05 compared with control; †p < 0.05 compared with fibrinogen cases. Roles of αvβ3 and ICAM-1 in different phases of adhesion of PMNs to Lu1205 cells under shear rate of 62.5 s⁻¹ (B) or 20 s⁻¹ (C). Values are means ± SEM (n = 3). *p < 0.05 compared with fibrin only cases. D, PMNs bind weakly to nonmetastatic melanoma cell line WM35. Values are means ± SEM (n = 3). *p < 0.05 compared with fibrinogen cases. E, Lu1205 adhesion efficiency for >1 s (initial tethering), 3 s (transient adhesion), and 5 s (long-term adhesion) as a result of Lu1205 and PMN collisions: role of soluble fibrin(ogen) on melanoma adhesion efficiency to EI cells via PMNs with shear rate of 62.5 s⁻¹ (E). Roles of αvβ3 and ICAM-1 in Lu1205 adhesion at the shear rate of 62.5 s⁻¹ (F). *p < 0.05 compared with the Lu1205+Fn case. Values are mean ± SEM (n = 3).
has first shown that thrombin-regulated Fn formation can enhance PMN and melanoma cell aggregation under flow conditions. An earlier study reported that soluble Fn would actually reduce the monocyte adherence to A375 melanoma cells under flow conditions (22). However, there are several differences between these studies and the current work. The melanoma cell line A375 used in Biggerstaff et al. (22) was reported to express ICAM-1 but not \( \alpha_\beta_3 \), whereas Lu1205 cells used in the current study express \( \alpha_\beta_3 \) in addition to ICAM-1, which was shown to have a high affinity for fibrin(ogen)-mediated firm adhesion of melanoma cells. In addition, experimental methods used in Biggerstaff et al. (22) were different from the current study. In Biggerstaff et al. (22), monocytes were perfused over tumor cell monolayer for 1 h in a parallel-plate flow chamber. In contrast, we quantified PMN–Lu1205 heterotypic aggregation within short time periods (several minutes). In a cone-plate assay, both Fn and Fg were able to significantly enhance aggregation between \( \alpha_\beta_3 \)-blocked Lu1205 cells and PMNs within 5 min shear (Fig. 6A–C). By 60 s, Fn and Fg increased percentage of aggregation from 45 to 60%; by 5 min, Fn and Fg increased percentage of aggregation from 27 to 37 and 35%, respectively. This result implies that Fg promotes Mac-1/ICAM-1 bond formation by possibly adding extra binding sites between Mac-1 and ICAM-1. However, during the long-term shear, Mac-1/ Fn/ICAM-1 bonds dissociate (22). Without \( \alpha_\beta_3 \), Fn-occupied ICAM-1 or Mac-1 could become obstacles to normal Mac-1/ICAM-1 bond formation, thereby reducing aggregation.

**\( \alpha_\beta_3 \) integrin contributes to fibrin-mediated prolonged stable adhesion between melanoma cells and PMNs**

Melanoma cells do not express selectins or sLe\(^a\) sugar groups at the levels necessary for cells to attach to the endothelial wall under venous flow conditions. Recent studies have shown that fibrinolytic factors and Fn deposition were both associated with hemagenous metastasis of murine melanoma cells (7). Fn is likely to be deposited on the surface of endothelium or platelets upon inflammation or tissue damage. Melanoma cells attach to Fg via \( \alpha_\beta_3 \) and \( \alpha_\beta_1 \) to von Willebrand Factor via \( \alpha_\beta_3 \) and to fibronectin via \( \alpha_\beta_3 \), \( \alpha_\beta_3 \), and \( \alpha_\beta_1 \), respectively, under static conditions. In addition, the current study using a parallel-plate flow chamber to examine Lu1205 melanoma cells binding to immobilized fibrin (ogen) has indicated that \( \alpha_\beta_3 \) was a major contributing receptor for Fg and Fn binding especially under low shear rates, which agrees well with a previous study on M21 melanoma cells adhesion to fibrin(ogen) (11). More importantly, melanoma cells could engage with fibrin(ogen) firmly without apparent cell rolling, which is potentially important for the arrest of sLe\(^a\)-negative melanoma cells the endothelial cells under venous flow conditions.

The expression of \( \alpha_\beta_3 \) is associated with malignant phenotype of tumor, which promotes tumor cells, ECs, and fibroblast migration and invasion by interacting with fibrin(ogen) and its plasminogen-lytic products (36, 37). When \( \alpha_\beta_3 \) on melanoma cells were blocked, Fn-mediated sustained aggregation between melanoma cells and PMNs was almost obligated. This demonstrated that \( \alpha_\beta_3 \) have a high affinity for Fn-mediated stable-firm adhesion between PMNs and melanoma cells under hydrodynamic conditions. The high affinity of \( \alpha_\beta_3 \) for fibrin(ogen) is evident from biochemical and structural analysis. There are three putative \( \alpha_\beta_3 \) binding sites on Fg (13), which are RGDS at the C terminus of \( \alpha_\beta_3 \)-chain 572–575, RGDF at N terminus of \( \alpha_\beta_3 \)-chain 95–98, and dodecapeptide at the C terminus of \( \gamma_\beta_3 \)-chain 400–411. These domains bind to immobilized \( \alpha_\beta_3 \) so strongly that they do not dissociate once they bind. In particular, RGDS site at 572–575 has stronger affinity for \( \alpha_\beta_3 \) than dodecapeptide. Thrombin treatment of Fg on its \( \alpha_\beta_3 \)-chain may induce conformational change and expose these RGD sites that are inaccessible to integrins in native structures. In addition, fibrin(ogen) may activate \( \alpha_\beta_3 \) and induce cluster of integrins on cell–cell contact regions, further increasing the stability of cell aggregates (38). In agreement with our heterotypic aggregation studies and model about fibrin(ogen)-mediated PMN-dependent melanoma adhesion, soluble Fg enhanced the melanoma cell arrest to immobilized Fg, serving as a cross-linking ligand for \( \alpha_\beta_3 \) between attached and circulating tumor cells (11). More in-depth kinetic analysis of \( \alpha_\beta_3 \)-fibrin(ogen) interaction is needed to better understand the bond strength.

**Mac-1 on PMNs serves as a counterreceptor for ICAM-1 and fibrin(ogen)**

Mac-1 on leukocytes, especially PMNs, is a high affinity receptor for fibrin(ogen), mediating PMN adhesion to inflamed ECs (39). Previously, Mac-1 was shown to mediate PMN homotypic aggregation under venous flow conditions (40). The current study demonstrates that Mac-1 also played roles in Fg-mediated heterotypic aggregation between melanoma cells and PMNs. Fg contains many recognition sites for Mac-1 within D domain, including two peptide sequences, \( \gamma_190–202 \) and \( \gamma_377–395 \) (41), which are called P1 and P2. Mac-1 may noncovalently bind to sites other than P1 and P2 (42). However, Mac-1 has stronger avidity for soluble Fn or immobilized Fg. This was suggested by the cryptic theory where pulling out P2 region from the central domain of Fg \( \gamma \)-module would regulate the binding affinity of Fg for Mac-1. This partially explains our melanoma–PMN aggregation results showing that Fn mediates stronger binding than Fg does. Although some studies also showed that PMNs have a higher possibility to form long-lasting bonds with immobilized ICAM-1 than immobilized Fg (27), we cannot rule out the possibility that Fn could enhance PMNs and tumor cell binding by inserting additional bonds between Mac-1 and ICAM-1 instead of replacing the existing bonds.

Collectively, our study demonstrated that PMN could tether melanoma cells to the vascular endothelial wall through the formation of shear-resist bonds. The most intriguing part of the current study is to demonstrate how a tumor microenvironment affects immune cell responses and cancer cell adhesion, especially when being subject to thrombin-regulated fibrin(ogen) immunoeediting. This is one of several possible settings in which tumor cells can capitalize on hemostatic components for the metastasis. This study has shed light on possible molecular mechanisms in fibrin(ogen)-
mediated PMN–melanoma interactions under flow conditions and potential therapeutic importance of Fn receptors in melanoma cell adhesion.

Potential roles of selectin ligands, P-selectin, l-selectin, and VCAM-1 on melanoma cell adhesion

Conventionally, the binding of P-selectin to leukocytes requires sialylated and fucosylated carbohydrates on PSGL-1. This binding is supported by sLe^a-like motifs on O-linked glycans of PSGL-1. Analysis of human metastatic melanoma lesions showed an elevated expression of sLe^a and sLe^x (43). However, further exploration of the interaction between melanoma and ECs revealed that melanoma may use other proteoglycan and oligosaccharide to bind to P-selectin and E-selectin, including heparin sulfate under flow (44). Using mAbs failed to detect any apparent expression of sLe^a on small cell lung cancer and neuroblastoma cells (45). Therefore, it is of interest to compare PMN-mediated, Fn-mediated, and selectin-mediated melanoma adhesion to ECs under flow. From our adhesion studies using parallel-plate assays, most melanoma arresting onto the EI monolayer were associated with PMNs. In addition, Fn enhanced PMN-facilitated melanoma adhesion in higher magnitude than did melanoma direct adhesion to ECs (data not shown). Despite importance of PMN and Fn, selectins and VCAM-1 on ECs should not be ignored. VLA-4, which is expressed by melanoma, has ligand VCAM-1 on ECs.

Upregulation of VCAM-1 expression was associated with increased experimental metastasis in vivo (46, 47). VCAM-1/VLA-4 interaction-mediated melanoma adhesion to ECs under low shear condition (48, 49). Surprisingly, a high level of VLA-4 may restrict cells to detach as a prelude to invasion, thereby inhibiting tumor cell metastasis. Selectin roles in melanoma metastasis were also demonstrated in animal models. For example, l-selectin plays a role in nonlymphoma tumor cell localization to lymph node (50). Although P-selectin was traditionally considered as a receptor for platelet-melanoma binding, its role in EC–melanoma binding was studied in P-selectin-deficient mice in which lung metastasis was significantly attenuated (51).

Tether behavior exhibited by fibrinogen–ICAM-1 bonds may be an indication that in absence of selectin ligands, melanoma cells may explore other mechanisms for their successful transmigration. There have been no biomechanical models or biochemical basis for this interaction so far. Fast association and dissociation rates are prerequisites for PSGL-1–P-selectin–mediated PMN tether to ECs under flow conditions. Such a rapid kinetic property was not witnessed in Mac-1/Fn and l-selectin under flow conditions. Such a rapid kinetic property was not witnessed in Mac-1/Fn and l-selectin under flow conditions. Therefore, it is of interest to compare PMN-mediated, Fn-mediated, and selectin-mediated melanoma adhesion to ECs under flow. From our adhesion studies using parallel-plate assays, most melanoma arresting onto the EI monolayer were associated with PMNs. In addition, Fn enhanced PMN-facilitated melanoma adhesion in higher magnitude than did melanoma direct adhesion to ECs (data not shown). Despite importance of PMN and Fn, selectins and VCAM-1 on ECs should not be ignored. VLA-4, which is expressed by melanoma, has ligand VCAM-1 on ECs. Although P-selectin was traditionally considered as a receptor for platelet-melanoma binding, its role in EC–melanoma binding was studied in P-selectin-deficient mice in which lung metastasis was significantly attenuated (51).

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Potential roles of receptors in melanoma metastasis

During their passage through the EC wall, tumor cells undergo extensive interactions with host cells including PMNs. PMNs cause a dense Fn accumulation around them under flow conditions with a platelet-independent mechanism in which Mac-1 may play a role (52). This may contribute to binding of melanoma to PMNs and arrest of melanoma to ECs. A dose- and time-dependent increase in ICAM-1 on melanoma by TNF-α treatment resulted in enhancement of in vivo metastasis (53). This TNF-α inducible increase in metastasis could be reversed by knocking down ICAM-1 on cell surface. Apparent contradictory results came from in vivo studies with ICAM-1 knockout mice, which showed that ICAM-1 deletion enhanced pulmonary metastasis (54, 55). However, this genetic deletion was conducted on the acceptor mice side but not on the melanoma side. Because T cells use receptors for ICAM-1 to bind/migrate into tissue and mediate tumor killing processes, reduced ICAM-1 expression may inhibit T cell migration and T cell–mediated tumor rejection. Most likely, the reduced tumor killing might compensate for the reduced tumor adhesion to ECs in ICAM-1 knockout mice, leading to the enhanced melanoma lesions observed in tissue outside the vasculature. A better understanding of involvement of receptors in melanoma adhesion to ECs via Fn and PMNs in circulation may come from examination of melanoma arrest within vasculature.

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Disclosures

The authors have no financial conflicts of interest.

References

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FIBRIN(OGEN) ENHANCES PMN ADHESION TO MELANOMA UNDER FLOW


molecular characterization of CD44-fibrin(ogen) binding: distinct molecular


