Role of LeuCAM Integrins and Complement in Platelet-Monocyte Rosette Formation Induced by Immune Complexes of Human Immunodeficiency Virus-Type 1-Immune Thrombocytopenic Purpura Patients

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Patients with human immunodeficiency virus-type 1-immune thrombocytopenic purpura (HIV-1-ITP) have elevated polyethylene glycol (PEG)-precipitable immune complexes (ICs) composed of IgG, IgM, and complement that are threefold to sevenfold higher than in healthy control subjects. These complexes contain anti-F (ab')$_2$ as well as anti-idiotypic antibodies versus anti-HIV-1gp120. Because anti-F (ab')$_2$ and anti-idiotypic antibodies correlate with thrombocytopenia ($r = .83$ [J Clin Invest 77:1756, 1988] and $r = .90$ [J Clin Invest 89:356, 1992], respectively) we studied the binding of ICs to platelets and monocytes as well as their role in platelet-monocyte rosette formation. ICs bind to platelets in a saturation-dependent manner (optimum at 10 µg/mL; 0.5% of serum conc). Binding to platelets could not be inhibited with platelet saturating concentrations of aggregated IgG or with monoclonal antibody (MoAb) IV.3 versus FcRrll. Platelet binding could be inhibited with Fab anti-C3, anti-C1q, or anti-C4 by 57%, 40%, and 46% respectively, not with control Fab ($P < .001$). Monocytes from HIV-1-ITP patients form rosettes with normal platelets 16.8 ± 5.2 rosettes/100 monocytes compared with 4.8 ± 0.8 control monocytes plus normal platelets ($P = .009$). Gel-washed HIV-1-ITP platelets formed 19 ± 2.0 rosettes with U937 cells compared to 6.3 ± 1.0 for normal platelets ($P = .001$). Arming of U937 cells with HIV-1-ITP ICs (5 µg/mL) formed 36.7 ± 2.5 rosettes compared with 10.6 ± 1.2 for control ICs ($P < .01$). Rosetting of armed U937 cells could be inhibited with MoAbs versus the a chains of CD11a (LFA-1), 11b (Mac-1), or 11c (p150,95) by 67%, 70%, and 61%, respectively ($P < .007$), whereas binding of ICs to U937 cells was unaffected. Isotype-matched control as well as MoAbs versus antigens on U937 cells (CD13, CD33) or the anti-FcRrII receptor had no effect. However, Fab fragments of polyclonal anti-C3 inhibited rosette formation by 78% ($P < .01$); control Fab had no effect. Thus, platelet-monocyte rosette formation is not Fc dependent. It is complement receptor dependent and requires the cooperation of all three LeuCAM integrins.

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IMMUNE thrombocytopenia is a common hematologic complication of human immunodeficiency virus type 1 (HIV-1) infection. It shares laboratory and clinical features with classic autoimmune thrombocytopenic purpura (ATP) including increased levels of platelet-bound Ig, presence of normal or increased numbers of megakaryocytes in the bone marrow (BM), and improvement of thrombocytopenia following inhibition or ablation of the reticuloendothelial system (RES). HIV-1-immune thrombocytopenic purpura (HIV-1-ITP) differs from ATP in that levels of platelet-bound IgG, IgM, and complement are threefold to fourfold higher in patients with HIV-1-ITP compared to patients with ATP. Polyethylene glycol (PEG) precipitates of sera from HIV-1-ITP patients are composed of immune complexes (PEG-ICs) that are threefold to sevenfold higher than levels obtained in ATP patients; levels in ATP patients are no different from control subjects. PEG-ICs of HIV-1-ITP patients bind to platelets in a saturation-dependent manner. These immune complexes contain IgG, IgM, C3, and anti-HIV-1 gp120 anti-idiotypic complexes. Platelet-bound Ig from patients with HIV-1-ITP also contain IgG, IgM, and anti-HIV-1 gp120 anti-idiotypic complexes.

We have studied the role of PEG-ICs as mediators of binding of platelets to cells of the monocytic lineage. Our previous work has indicated a role for the β2 integrin Mac-1 in the binding of platelets to monocytes in the presence of serum IgG from patients with ATP. Our current experiments suggest that LeuCAM integrins on cells of the RES and complement-dependent bridging of platelets to RES cells may be important in the pathogenesis of HIV-1-ITP.

MATERIALS AND METHODS

Patients. Patients were recruited from New York University Medical Center. All patients had documented acquired immunodeficiency syndrome (AIDS)-defining illness. Preparation of PEG-ICs from patient and control sera. PEG-ICs were prepared as described, without 0.02% azide. These complexes contain IgG, IgM, C3, C4, C1q, and C4. The latter two components are present as determined by enzyme-linked immunosorbent assay (ELISA) with monospecific anti-sera on microtiter plates. Preparation of peripheral blood monocytes. Peripheral blood mononuclear cells (PBMC) were isolated from heparinized blood on Ficoll-Hypaque (Pharmacia, Piscataway, NJ), and monocytes isolated by adherence to plastic as described. Adherent cells (70% to 80% esterase positive) were adjusted to a concentration of 10⁶ cells/mL for use in the adhesion assay. Highly purified monocyte preparations were obtained by lysis of contaminating B cells with anti-IgM and complement as described.

Cell culture. U937 cells (human histiocytic lymphoma; American Type Culture Collection [ATCC], Rockville, MD) were grown in RPMI 1640 (GIBCO, Grand Island, New York) supplemented with 10% fetal calf serum (FCS; GIBCO) at 37°C in 5% CO₂. The cells

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were passed every 72 hours at a 1:10 dilution; cells were used in the rosette assay after 72 hours in culture. Cell viability was greater than 90% as determined by Trypan blue exclusion.

Preparation of platelets. Platelets were isolated from blood anticoagulated with 0.38% sodium citrate. Platelet-rich plasma (PRP) was obtained by centrifugation of blood at 320g and applied to a Sepharose 2B column (Pharmacia) equilibrated with phosphate-buffered saline (PBS)-citrate. Platelet concentration was adjusted to 10^7/mL.

Preparation of armed U937 cells. U937 cells were recovered from culture, washed twice in RPMI/FCS, adjusted to a concentration of 10^6/mL, and incubated with PEG-ICs (5 µg/mL) from HIV-1-ITP patients or control subjects for 1 hour at 4°C. The cells were washed twice in RPMI/FCS and resuspended at a concentration of 10^6/mL.

Preparation of aggregated IgG. Diethyl aminoethyl cellulose (DEAE)-purified IgG was heated at 56°C for 60 minutes before utilization.

Rosette assay. Fifty microliters of monocyte or armed U937 cell suspension (10^5/mL) and 20 µL of platelet suspension (2.5 x 10^8/mL to give a monocyte:platelet ratio of 1:10) were combined in a microcentrifuge tube (Fisher, Pittsburgh, PA), centrifuged at 600g for 5 minutes, and incubated at 37°C for 1 hour. The supernatant was removed and replaced with 500 µL fresh RPMI/FCS. An aliquot was examined in a hemocytometer under phase microscopy, and the percentage of rosettes (U937 cells or monocytes with two or more adherent platelets) formed by U937 cells or monocytes enumerated.

Rosette inhibition experiments. One microgram of monoclonal antibody (MoAb) to the α chains of the Leu-CAM family of integrins (Mo 1 [anti-CD11b; Ortho Diagnostics, Raritan, NJ], LFA-1 [anti-CD11a; AMAC, Westbrook, ME], p150,95 [anti-CD11b, Becton Dickinson, Mountvale, CA]), or to the β2 chain of the same integrin family (60.3, anti-CD18, gift of Dr John Harlan, University of Washington, Seattle) was added to armed, washed U937 cells for 1 hour at 4°C before the addition of platelets as described above. In control experiments, identical amounts of antibodies with known affinity for cells of monocytic lineage, My7 and My9 (Coulter, Hialeah, FL), as well as isotype specific irrelevant monoclonals MOPC-21 (IgG1), MOPC-141 (IgG2b), and UPC-10 (IgG2a), (Sigma, St Louis, MO) were used. Fab fragments of anti-C3, anti-C4, and anti-C1q antibody were prepared from rabbit anti-C3 antiserum (a gift of Dr R.J. Looney, University of Rochester Medical Center, Rochester, NY).

Binding of PEG-ICs to platelets. Binding studies were performed as described previously with 125I-protein A. In some experiments the PEG-ICs were incubated with Fab fragments of anti-C3, anti-C4, or anti-C1q antibody, 80 µg/mL, or control Fab fragments at the same concentration for 1 hour at room temperature before addition to platelets. In other experiments PEG-ICs were added to platelets before and after the addition of aggregated IgG or MoAb IV.3 (anti-FeRγII). In another set of experiments saturating concentrations of heat aggregated IgG (40 µg/mL) or an equal volume of buffer were added to the platelets adsorbed to plastic, before the addition of serial dilutions of 125I-PEG-ICs obtained from HIV-1-ITP patient sera.

Binding of PEG-ICs to U937 cells. U937 cells (10^6) were incubated with PEG-ICs at concentrations of 5 to 100 µg/mL for 1 hour at 4°C and washed in PBS. PEG-IC binding to U937 cells was assayed by indirect immunofluorescence in a flow cytometer (FACScan; Becton Dickinson) using fluorescein isothiocyanate (FITC)-labeled F(ab')2 fragments of goat anti-human IgG (Sigma) and 1% formalin fixation. In other experiments MoAbs against CD11a, CD11b, CD11c, or isotype-matched controls (1 µg/mL), or Fab fragments of polyclonal anti-C3, anti-C4, or anti-C1q antibody (80 µg/mL) or control Fab fragments at the same concentration were added to the U937 cells for 1 hour at 4°C before the addition of the PEG-ICs. Results were expressed as an increase over background fluorescence by comparing mean peak fluorescence.

RESULTS

Platelet rosette formation with freshly isolated monocytes and platelets from HIV-1-ITP patients. Freshly isolated monocytes from patients with HIV-1-ITP were incubated with washed, control platelets and rosettes were enumerated. Patient monocytes formed 16.8 ± 5.2 rosettes/100 monocytes or C1q antiserum (Atlantic Antibodies, Stillwater, MN) by DEAE cellulose chromatography, papain digestion, and staphylococcal protein A affinity chromatography and used at 50 µg/mL. Control Fab fragments were similarly prepared from nonimmune rabbit or goat sera. Anti-FeRγII MoAb IV.3 was a gift of Dr R.J. Looney (University of Rochester Medical Center, Rochester, NY).

Fig 2. Effect of PEG-ICs of HIV-1-ITP patients on arming of U937 monocytes to form monocyte-platelet rosettes. U937 cells were armed with PEG-ICs (5 µg/mL) from HIV-1-ITP patients or control subjects (n = 28) or control subjects (n = 22), washed, and incubated with control gel washed platelets at a ratio of 10:1 (platelets: U937 cells). The cells were pelleted, incubated at 37°C for 1 hour, and rosettes counted by phase microscopy.
HIV-1-ITP PLATELET-MONOCYTE ROSETTE FORMATION

Fig 3. Effect of anti-LeuCam and anti-FcRγII receptor antibodies on U937 monocyte-platelet rosette formation. U937 cells were armed with HIV-1-ITP or control PEG-ICs and incubated with MoAbs against the α chain of the LeuCAM integrins LFA-1, Mac-1, or p150,95 (CD11a, 11b, or 11c, respectively), the β2 chain of the leu-CAM integrins (CD18), the subclass specific controls (MOPC-21, MOPC-141, and UPC-10), the myelomonocytic antigens (My7 and My9), n = 4, or the FcRγII receptor (IV.3), n = 3, before the addition of control gel-washed platelets.

Platelet rosettes. To determine whether PEG-ICs of HIV-1-ITP patients were qualitatively different from PEG-precipitable material of control subjects, both were incubated with U937 cells and platelet rosette formation enumerated. U937 cells armed with PEG-ICs (5 μg/mL) from patients with HIV-1-ITP formed 36.7 ± 2.5 rosettes/100 U937 cells (n = 28) with control gel-washed platelets from 12 different control subjects, whereas U937 cells armed with control PEG-ICs at the same concentration formed 10.6 ± 1.2 rosettes/100 U937 cells (n = 22, P < .01) (Fig 2). Thus, PEG-ICs of HIV-1-ITP patients are qualitatively different from PEG-precipitable material of control subjects with respect to their ability to bind to platelets.

Effect of anti-β2 integrin and anti-FcRγII antibodies on rosette formation. Because previous studies had shown a role for the β2 integrin Mac-1 in the binding of platelets to monocytes in ATP patients in the presence of their serum IgG, we examined the role of β integrins in HIV-1-ITP immune complex-induced rosette formation. Armed U937 cells were incubated with MoAbs against the α chains of the Leu-CAM family of integrins (CD11a, 11b, and 11c), the β2 chain of the LeuCAM family of integrins (CD18), the FcRγII (CDw32) receptor (IV.3) or against the control myelomonocytic antigens My7 and My9 (CD13 and CD33), or against isotype-matched control MoAbs (MOPC-21 [IgG1], MOPC-141 [IgG2b], and UPC-10 [IgG2a]) before the addition of control gel-washed platelets. Antibodies against CD11a, CD11b, and CD11c reduced rosette formation by 67%, 70%, and 61%, respectively (P < .007), for each positive control rosette formation (Fig 3). Surprisingly, IV.3, the MoAb against FcRγII had no effect (Fig 3). Isotype-matched control MoAbs reduced rosette formation by less than 3%. Anti-CD13 and CD33 (antibodies against non-integrin antigens found on U937 cells) reduced rosette formation by 14% and 33%, respectively (P = .1, n = 4, data not shown). Thus, LeuCAM receptor occupancy inhibits rosette formation, whereas FcRγII occupancy does not.

Effect of antibody against C3/C3bi. Because PEG-ICs of HIV-1-ITP patients contain C34 and because Mac-1 and p150,95 are receptors for C3bi, we examined the role of C3 receptor binding in rosette formation. U937 cells that had been armed with control and HIV-1-ITP PEG-ICs were in-

(mean ± SEM, n = 6) while similarly prepared control monocytes produced 4.8 ± 0.8 rosettes (n = 6, p = .009, Student's t-test) (Fig 1).

Freshly isolated gel-washed platelets from patients formed 19 ± 2.0 rosettes/100 U937 cells, while control platelets formed 6.3 ± 1.0 rosettes/100 U937 cells (P = .001, n = 4) (Fig 1).

Because these monocytes and platelets were obtained from patients with high levels of circulating immune complexes, we investigated if these complexes were involved in rosette formation.

Dose response of PEG-ICs on rosette formation. Armed U937 cells were incubated with platelets using concentrations of PEG-ICs ranging from 1 to 20 μg/mL. Optimum rosette formation (45/100 U937 cells) occurred at a PEG-IC concentration of 5 μg/mL (n = 4). This was 3.6-fold greater than the binding of PEG precipitable material from control subjects at 5 μg/mL.

Effect of PEG-ICs of HIV-1-ITP patients versus control subjects on arming of U937 monocytes to form monocyte-

PEG Protein μg/ml

Fig 4. Binding of PEG-ICs to platelets. HIV-1-ITP patient (●—●) or control (○—○) PEG-ICs were serially diluted from 50 to 1 μg/mL and incubated with gel-washed platelets adsorbed to plastic microtiter plates. The adsorbed platelets were washed, and bound IgG detected by 125I-staphylococcal protein A.

PEG-IC's
LFA-1
Mac-1
p150,95
CD18
FcRγII
My7
My9
IgG1 Control
IgG2a Control
IgG2b Control

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Fig 5. Effect of aggregated IgG or MoAb IV.3 (against FcRγII) on binding of PEG-ICs to platelets. (A) Platelets were adsorbed to microtiter plates as described and then incubated with buffer or aggregated IgG at 40 μg/well for 1 hour at room temperature before the addition of serial dilutions of 125I-PEG-ICs, starting at 50 pg/well. Inset documents saturation binding of aggregated IgG to platelets at 40 μg/well (monitored with 125I-staphylococcal protein A [SPA]). (B) Platelets were adsorbed to microtiter plates and then incubated with buffer or a saturating concentration of IV.3 (5 μg/mL) before the addition of serial dilutions of PEG-IC starting at 400 ng/well. Binding was monitored with 125I-SPA. Control binding of 125I-SPA plus platelets or platelets plus IV.3 was 1.4 X 10^3 cpm.

To better understand the mechanisms of platelet-monocyte rosette formation, we investigated the interaction of PEG-ICs with platelets and with U937 cells.

**Binding of PEG-ICs to platelets.** Binding of PEG-ICs to platelets is concentration-dependent and saturable with optimum binding occurring at a PEG-IC concentration of 10 μg/mL (Fig 4). Because the serum concentration in HIV-I-ITP patients is 0.7 to 1.5 pg/mL, the saturating concentration is pathophysiologically relevant.

**Binding of PEG-ICs to platelets is not Fc receptor dependent.** Because of the unexpected finding that anti-FcγRII receptor antibody did not inhibit rosette formation, we elected to independently confirm that PEG-IC binding to platelets was not Fc receptor dependent. Figure 5A shows the lack of inhibition of 125I-PEG-IC binding to platelets by a platelet-saturating concentration of aggregated IgG (inset of figure). Similar negative results were obtained with a platelet-saturating concentration of MoAb IV.3 against the platelet FcγRII receptor (Fig 5B).

**Inhibition of binding of PEG-ICs to platelets with anti-C3, anti-C1q, and anti-C4 antibody.** Because anti-C3 antibody inhibited rosette formation, we elected to determine whether its effect was on binding of PEG-ICs to platelets. Figure 6 shows that incubation of PEG-ICs with Fab anti-C3 at ratios...
Fig 6. Effect of preincubation of PEG-ICs with Fab anti-C3 antibody on binding to platelets. HIV-1-ITP PEG-ICs were applied to control gel-washed platelets adsorbed to plastic microtiter plates alone (■ - ■) or following preincubation of the PEG-ICs with Fab fragments of control rabbit IgG at a 1:10 weight ratio (PEG-ICs: Fab fragments) (○ - ○), or Fab fragments of rabbit IgG anti-C3 at 1:5 (□ - □) or 1:10 (▲ - ▲) ratios. The adsorbed platelets were washed, and bound IgG detected by 125I-staphylococcal protein A (n = 2).

Effect of Fab anti-C3 and anti-C4 on binding of PEG-ICs to U937 cells. Because Fab anti-C3 inhibited rosette formation as well as binding of HIV-1-ITP PEG-ICs to platelets, we elected to determine whether anti-C3 as well as anti-C4 would also inhibit binding to U937 cells. Table 1 shows 44% to 42% inhibition of binding of PEG-ICs to U937 cells following preincubation of ICs with Fab anti-C3 or anti-C4, respectively (P < .001, n = 4). Negligible inhibition was noted with nonimmune Fab.

**DISCUSSION**

These studies provide the first direct evidence of increased platelet-monocyte interaction mediated by the unique immune complexes produced by patients with HIV-1 infection. PEG-ICs from HIV-1-ITP patients are 3.4-fold more potent in inducing platelet U937 cell rosette formation than control PEG-precipitates of normal subjects. Because these complexes are present in threefold to sevenfold greater concentration in the sera of HIV-1-ITP patients compared with control subjects and the optimum in vitro concentration for platelet-monocyte rosette formation is 70- to 150-fold less than

| Table 1. Effect of Anti-C3 and Anti-C4 Fab on Binding of PEG-ICs to U937 Cells |
|--------------------------------|----------------|----------------|----------------|
| *PEG Concentration, µg/mL*    | Control       | Patient        | Patient + antibody   |
|                               | 0             | 5              | 10              | 50             | 100            |
| Control                       | 1.6 ± 0.5     | 2.1 ± 1.7      | 1.8 ± 1.3       | 2.2 ± 1.5      |                |
| Patient + anti-C3             | 1.6 ± 3.3     | 2.3 ± 0.6      | 5.4 ± 0.4       | 7.7 ± 0.1      |                |
| Patient + anti-C4             | 0.56 ± 0.05   | 0.58 ± 0.04    | 0.86 ± 0.08     | 0.96 ± 0.14    | 0.85 ± 0.06    |
| Control + anti-C3             | 0.96 ± 0.14   | 0.96 ± 0.14    | 0.96 ± 0.14     | 0.85 ± 0.06    | 1.18 ± 0.04    |
| Control + control antibody    | 1.18 ± 0.04   |                |                |                |                |

U937 cells (10⁶/mL) were incubated with various concentrations of patient or control PEG-ICs and binding detected by fluorescence flow cytometry with FITC-labeled Fab, fragments of goat anti-human IgG. In some experiments 100 µg of Fab fragments of anti-C3 or anti-C4 were incubated with PEG-ICs in 100 µL for 1 hour at 4°C before the addition of 0.9 mL of 10⁶ U937 cells for an additional 1 hour at 4°C. Relative fluorescence and SEM is given for 0, 5, 10, 50, and 100 µg/mL. The relative percentage of positive or negative control is given for 20 µg/mL, n = 4. *P < .001.
the serum concentration, these complexes are both qualitatively and quantitatively favored to mediate platelet-monocyte interaction in vivo, which could contribute to thrombocytopenia. This hypothesis should be interpreted with caution because there is no correlation between platelet count and PEG-precipitable immune complex level or platelet-associated IgG. It is possible that the presence of these immune complexes more directly reflects the disorder of immune regulation rather than the thrombocytopenia. However, it is also possible that the qualitative composition of the immune complex may be more directly related to the thrombocytopenia. This appears to be the case. We have recently demonstrated the presence of anti-idiotype-anti-HIV-1 gp120 antibody in the PEG-immune complexes and platelet eluates of HIV-1-ITP patients. Serum anti-idiotype HIV-1 gp120 antibody correlated strongly with thrombocytopenia, and it is also possible that the qualitative composition of the immune complex is of particular interest that occupancy of all three receptors inhibited rosette formation. Yet binding of PEG-ICs to U937 cells appears to be complement-mediated because anti-C3 Fab fragments inhibited platelet-monocyte rosette formation, and anti-C3b, anti-C4, and anti-C1q Fab inhibit binding of PEG-ICs to platelets. It is of interest in this regard that platelets have a C3b/C3bi (gp 45 to 70) receptor, a Clq receptor, as well as a recently described complement receptor 4 (CR4). The binding of HIV-1-ITP PEG-ICs to platelets is surprisingly not FcγRII-mediated. This was established by demonstrating that binding was not inhibited by aggregated IgG or MoAb IV.3 against the FcγRII receptor, under saturating conditions of binding of aggregated IgG and IV.3 to platelets. Rather, the binding of HIV-1-ITP PEG-ICs to platelets appears to be complement-mediated, because anti-C3 Fab fragments inhibited platelet-monocyte rosette formation, and anti-C3b, anti-C4, and anti-C1q Fab inhibit binding of PEG-ICs to platelets. It is of interest in this regard that platelets have a C3b/C3bi (gp 45 to 70) receptor, as well as a recently described complement receptor 4 (CR4). The binding of HIV-1-ITP PEG-ICs to U937 monocytes is also not FcγRII-mediated because IV.3 did not inhibit rosette formation. Rather, the binding appears to be complement-mediated because anti-C3b and anti-C4 Fab inhibited binding of PEG-ICs to U937 cells.

Increased expression of β2 integrins has been observed in U937 monocytes after HIV-1 incubation. Therefore, it is of particular interest that occupancy of all three β2 receptors with either of the specific anti-functional antibodies for LFA-1, Mac-1, or p150,95 or an MoAb reacting with the β2 subunit of all three receptors inhibited rosette formation. Yet binding of PEG-ICs to U937 cells was not inhibited by any of these MoAbs. Thus, neither Mac-1 nor p150,95 is acting as a complement receptor for the PEG-ICs. The mechanism of inhibition of rosette formation by LeuCAM receptor occupancy is yet to be elucidated. It is unlikely that all three receptors are required on U937 cells for binding to platelets. Indeed, the counter-receptor for LFA-1 (ICAM-1) is not present on platelets. It is more likely that receptor occupancy has an inhibitory effect on U937-monocyte function. Gresham et al. have reported elevated cyclic adenosine monophosphate (AMP) levels in immune complex-stimulated neutrophils treated with anti-CD11b (Mac-1) or CD18 (β2 subunit). They also noted that inhibition of phagocytosis of opsonized erythrocytes with anti-CD18 could be overcome with a cyclic AMP inhibitor, HA1004, which inhibits protein kinase A. It is likely that similar effects may be occurring with U937 cells treated with anti-LeuCAM antibodies.

Regardless of the mechanism, it is clear that platelet-monocyte rosette formation induced by PEG-ICs can be regulated by LeuCAM receptor occupancy and requires complement for platelet-monocyte bridging. Modulation of LeuCAM integrins or complement receptors on platelets or cells of the RES may provide therapeutic approaches for the treatment of HIV-1-ITP.

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