Role of glycocalyx in leukocyte-endothelial cell adhesion

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Mulivor, A. W., and H. H. Lipowsky. Role of glycocalyx in leukocyte-endothelial cell adhesion. Am J Physiol Heart Circ Physiol 283: H1282–H1291, 2002.—The binding of fluorescently labeled microspheres (FLMs, 0.1-μm diameter) coated with antibody (1α29) to ICAM-1 was studied in postcapillary venules during topical application of the chemoattractant N-formylmethionyl-leucyl-phenylalanine (fMLP). FLM adhesion to endothelial cells (ECs) increased dramatically from 50 to 150 spheres per 100-μm length of venule after superfusion of the mesentery with fMLP and equaled or exceeded levels of leukocyte (WBC) adhesion. Removal of the EC glycocalyx by micropipette infusion of the venule with heparinase increased FLM-EC adhesion to levels attained with fMLP. Subsequent application of fMLP did not increase FLM adhesion further, suggesting that the FLMs saturated all ICAM-1 binding sites. Percussion with heparinase after superfusion with fMLP significantly increased FLM-EC adhesion above levels attained with fMLP. However, WBC adhesion fell because of possible removal of selectins necessary to maintain WBC rolling at the wall. It is concluded that the glycocalyx serves as a barrier to adhesion and that its shedding during natural activation of ECs may be an essential part of the inflammatory response.

endothelium; heparinase; N-formylmethionyl-leucyl-phenylalanine

MICROVASCULAR ENTRAPMENT and diapedesis of leukocytes (WBCs) in the inflammatory process revolves around a well-defined sequence of events that encompass the radial migration (margination) of WBCs toward the endothelium (26), selectin-mediated rolling along the venular wall (24), and integrin-mediated firm adhesion of WBCs to the endothelium (10). Direct observations by intravital microscopy of WBC rolling along endothelial cells (ECs) and adhesion in postcapillary venules have provided much quantitative data on the strength of WBC-EC bonds and the receptor-ligand pairs involved. A common approach to these studies has been to apply various stimuli to promote WBC-EC interaction and to measure the rolling velocity of WBCs or the number of cells firmly adhered to quantitate hydrodynamic forces acting to dislodge WBCs from the EC. For example, the pioneering studies of Atherton and Born (3) used exposure of the mesenteric tissue to mechanical handling and inflammatory agents (e.g., caseine and histamine) and recorded WBC rolling velocity and numbers of firmly adhered cells to quantitate the extent of WBC-EC adhesion. Subsequent studies examined rolling and adhered WBCs in exteriorized microvascular preparations to elucidate the role of various chemotactants and cytokines in stimulating adhesion, such as leukotriene B4 (2), platelet-activating factor (4), tumor necrosis factor (TNF)-α (15), and formyl peptide N-formylmethionyl-leucyl-phenylalanine (fMLP) (11, 22), to name a few. Most in vivo studies of this type have recognized the potential of these agents to activate both the WBC and the EC; however, attempts to systematically activate these cells individually have not been performed. To address this void in the literature, the present study was undertaken to examine the adhesion of inert polystyrene microspheres coated with MAb to adhesion molecules on the endothelium, principally ICAM-1 (CD 54) during topical application of fMLP to intestinal mesentery.

The initial objective of the present study was to compare the rates of sequestration of systemically infused MAb-coated spheres, 0.1 μm in diameter, to those of WBCs, to thus test the hypothesis that WBC-EC adhesion is dominated by the process of WBC activation by superfusion with fMLP. To that end, studies were first performed to determine the appropriate concentration of microspheres to minimize concentration effects. Spheres were subsequently infused at a steady rate into the femoral vein, and their adhesion to the walls of postcapillary venules was evaluated under resting (control) conditions and in response to superfusion with fMLP. On finding that the transient increase in sphere adhesion in response to fMLP was similar in magnitude to that of WBC-EC adhesion and that the spatial distribution of adherent spheres was limited to focal adhesion sites because of their apparently restricted access to the EC, we conducted additional studies to elucidate the role of the endothelial glycocalyx in modulating adhesion events of spheres and WBCs. For this purpose, individual postcapillary venules were cannulated with micropipettes, perfused with heparinase to remove the glycocalyx, and then subjected to a steady influx of spheres from the pipette or WBCs from proximal microvessels.

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METHODS

Animal Preparation and Intravital Microscopy

Male Sprague-Dawley rats weighing 350–450 g were anesthetized with pentobarbital sodium (45 mg/kg ip), tracheostomized, and allowed to breathe spontaneously. The right internal jugular vein was cannulated with polyethylene (PE-50) tubing to enable administration of supplemental doses of anesthetic as required to maintain a surgical plane of anesthesia. The left carotid artery was cannulated with PE-90 tubing and connected to a strain gauge-type pressure transducer to monitor arterial blood pressure. To facilitate systemic infusion of fluorescently labeled microspheres (FLMs) the right femoral vein was cannulated with PE-10 tubing and connected to an infusion syringe pump (Harvard Apparatus, Holliston, MA). The systemic Hct (Hctsys), WBC count, and circulating FLM concentration ([FLM]circ) were measured by withdrawing 0.25 ml of blood through the carotid catheter. Leukocyte counts were obtained with a Coulter counter (model BV-10; Sutter Instrument, Novato, CA). The luminal diameter of the right femoral vein was measured by video microscopy (image-shearing monitor; IPM, San Diego, CA) calibrated against a stage micrometer.

Micropipette Preparation and Infusion Protocol

Glass capillary tubes with a 1-mm outer diameter and a 0.75-mm inner diameter (TW100F-6; World Precision Instruments, Sarasota, FL) were drawn into micropipettes with a vertical pipette puller (model 700-C; David Kopf Instruments, Tujunga, CA). For all animals studied, the WBC count averaged 7,682 ± 2,369 (SD) cells/μl and Hctsys averaged 46.7 ± 3.4 (SD%). FLM counts were obtained by using a hemocytometer while viewing under a fluorescence microscope.

The intestinal mesentery was exteriorized through a midline abdominal incision and placed on a glass pedestal to facilitate viewing under either brightfield microscopy by transillumination or incident illumination with a Ploemotype fluorescence illuminator with fluorescein excitation and emission filters. The tissue was suffused with HEPES-buffered Ringer solution (pH 7.4) at a temperature of 37.0°C. Solutions of IMLP (10−7 M; Sigma, St. Louis, MO) were prepared in HEPES-buffered Ringer solution (pH 7.4) for irrigation of the tissue.

Mesenteric postcapillary venules ranging in width from 25 to 50 μm were viewed with either a Leica UM ×20/0.33 numerical aperture (NA) (true magnification ×13/0.22 NA) or a Zeiss water-immersion ×40/0.75 NA objective. The image was projected onto a low-light-level silicon-intensified target camera (model 66; Dage-MTI, Michigan City, IN), for an effective width of the video field equal to 310 or 100 μm, respectively.

Fluorescent Microsphere Preparation

Fluorescent (yellow-green) carboxylate-modified polystyrene microspheres, 0.1 μm in diameter (Fluospheres; Molecular Probes, Eugene, OR), were labeled with 1a29 (IgG1) (26) MAb to rat ICAM-1 (a generous gift of Dr. Donald Anderson, Pharmacia and Upjohn Laboratories, Kalamazoo, MI). A nonreactive control MAb, Margl–2 (IgG1) mouse anti-rat, was obtained from Zymed Laboratories (San Francisco, CA) for determining binding specificity.

FLMs were prepared by first binding protein G (PG) as a functional spacer between the microsphere and the 1a29 MAb. PG was chosen because of its superior binding properties to mouse IgG1 antibodies compared with protein A and protein AG (1). This procedure entailed a two-step process. The first stage of the binding protocol involved binding the amine group on the PG to a carboxyl group on the FLM with carbodiimide (6). The carbodiimide reaction requires activation of the amine group on the PG at pH 8.5 and activation of the carboxyl group of the FLM at pH 4.5. The carbodiimide solution of 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide facilitated the reaction between the two activated functional groups.

The second stage of the binding protocol involved binding the Fc region of the 1a29 MAb to the free carboxyl end of the PG, leaving the functional Fab group available for binding to ICAM-1. The Fc region of the 1a29 contains several carbohydrate residues (13) that are ideal to bind the PG under mildly acidic conditions of pH 4–7. SDS-PAGE was performed to quantitate the extent of PG and 1a29 binding. The final supernatant of the sphere suspension revealed an absence of PG and 1a29 (<1 μg/ml), and calculations suggested a final binding ratio of 88 1a29 molecules/FLM.

Red Blood Cell Velocity and Volumetric Flow

The center line V_{RBC} in arterioles and venules was measured with the two-slit photometric technique (31) using a self-tracking correlator (27). The mean velocity of blood (V_{mean}) was calculated from the relationship $V_{mean} = V_{RBC}/1.6$ (16). The vessel diameter (D) was measured with video image shearing. Volumetric flow rate of blood in the venules was calculated as the product of $V_{mean}$ and the cross-sectional area, $\pi D^2/4$, assuming a circular cross section.

Experimental Protocols

Two separate protocols were employed. The first protocol entailed continuous infusion of 1a29-FLMs into the femoral vein at a concentration ranging from 0.5 to 5.7 × 10^8 spheres·ml−1·kg−1 at a rate of 0.02 ml/min to achieve a desired systemic concentration. The second protocol entailed intubating venules with micropipettes filled with either FLMs at the desired concentration or heparinase (1 U/ml in normal saline; Sigma) to strip off the venular glycocalyx. In the latter case, FLM and WBC adhesion were observed under control conditions and in response to superfusion of the
mesenteric with fMLP before and after removal of the glyco-
calyx.

For each protocol, the mesenteric tissue was allowed to
stabilize for 30 min before data acquisition. Unbranched
postcapillary venules, 25–45 μm in diameter, with lengths of
at least 150 μm were chosen for analysis. Micropipettes
were inserted into proximal side branches to permit perfusion of
the venule with FLMs, heparinase, or blood from proximal
microvessels.

Measurements

WBC and FLM adhesion. The numbers of WBCs and FLMs
firmly adhered were measured by frame-by-frame analysis of
video recordings and normalized in terms of the number
adhering per 100 μm of venule length. Adhered WBCs and
FLMs were judged to be firmly adhered if they remained
stationary for at least 5 s. All FLMs and WBCs were counted by
focusing the microscope objective above and below the
diametral plane.

WBC rolling flux and adhesion. The flux of WBCs rolling
along the venular endothelium was measured by frame-by-
frame analysis of video recordings and was normalized with
respect to the potentially maximal flux of WBCs carried
within the venular lumen by computing the fractional flux,
\( F_{WBC} \). \( F_{WBC} \) was calculated with established techniques (8) as the ratio of rolling flux (cells/min) to the product of
microvessel bulk flow (Q) and systemic leukocrit (Lct) divided by
WBC mean cell volume (mcv): \( F_{WBC} = (\text{rolling flux} \times
\text{mcv/Q} \times \text{Lct}) \).

RESULTS

Examination of Microsphere Specificity

Initial experiments were performed to test the speci-
cificity of the binding of the 1a29-FLM to the vascular
endothelium. FLMs representing different stages of the
antibody labeling protocol were infused systemi-
cally to test their respective specificity for binding to
the endothelium. Unaltered carboxylated spheres were
dialyzed against PBS and infused into the femoral
vein. These spheres immediately adhered to them-
se and to the vascular endothelium, causing vas-
cular stasis. Protein G-coated FLMs were infused sys-
temically at concentrations ranging from 1.1 to 8.5 \( \times
10^9/\text{mm}^3 \). These spheres adhered to the endothelium at
a level of 1.2 ± 0.7 (control conditions) to 2.5 ± 0.46
(fMLP superfusion) spheres per 100 μm of venule
length. FLMs were prepared with a control antibody
(Marg1–2) with the same isotype (IgG1) as the anti-
ICAM-1 1a29, but not the specificity. The Marg1–2
antibody was coated onto the FLMs with the same
protocol used for the 1a29 antibody. The results of the
Marg1–2 FLM adhesion revealed maximum values of
3.2 ± 0.52 (under control conditions) and 3.49 ± 0.42
spheres/100 μm (with fMLP superfusion). In all cases
the adhesion of the control FLMs was significantly less
than the adhesion of the 1a29-FLMs, which typically
ranged from 20 (control) to 150 (fMLP stimulated)
spheres/100 μm.

To determine whether the process of linking the
1a29 antibody to the microspheres affected the speci-
cificity of the sphere-bound 1a29 for ICAM-1, individual
venules (\( n = 10 \)) were intubated with micropipettes
and perfused with soluble 1a29 (1 mg/ml) in PBS for 10
min. These venules were then perfused with 1a29-
FLMs (10^7 spheres/mm^3) for 20 min, under conditions of
tissue superfusion with either Ringer solution (control)
or fMLP. After perfusion with soluble 1a29, adhe-
sion levels equaled 2.41 ± 2.0 (SD) spheres/100 μm and
4.0 ± 1.5 spheres/100 μm, respectively. In similar
experiments (\( n = 10 \)) without perfusion with soluble
1a29, a significant level of adhesion was found to equal
67.3 ± 4.3 spheres/100 μm with Ringer superfusion,
and 163.5 ± 4.5 spheres/100 μm after fMLP superfu-
sion (\( P < 0.001 \)). Thus, although there was a signifi-
cant level (\( P < 0.001 \)) of nonspecific adhesion, it
amounted to <4% of that observed without perfusion
with soluble 1a29.

Systemic FLM Infusion

To determine the optimum circulating concentration
of 1a29-FLMs, different concentrations ([FLM]circ) of
spheres were infused via the femoral vein (syringe pump) to
achieve concentrations of 1.11, 2.43, 4.32, 8.46, and
10.87 ± 0.610^9/mm^3. Representative images of a postcap-
illary venule (D = 36.2 μm) with [FLM]circ = 4.32 ±
10^9/mm^3 are presented in Fig. 1 under control condi-
tions and after 42-min supphusion with fMLP. The brightfield images (Fig. 1, A and C) reveal the expected
dramatic rise in WBC adhesion from ~1 to 20 WBCs/
100 μm. The fluorescence images (Fig. 1, B and D) reveal a rise in FLM adhesion from 12 to 13 spheres/ 100 μm in response to the fMLP. The distribution of
FLMs was easily discernible under fluorescence mi-
roscope despite the occurrence of blurring of out-of-
focus spheres. By focusing the microscope up and
down, the presence of adhered spheres could be readily
evaluated. As in the case of the WBCs, the distribution of
adherent FLMs appeared patchy and confined to
discrete regions along the length of the vessel. How-
ever, the majority of FLMs appeared to be distributed
without interfering with WBC adhesion, and there
does not appear to be a shortage of binding sites for
the spheres caused by adherent WBCs.

The transient process of WBC and FLM adhesion to
the endothelium is illustrated in Fig. 2. Infusion of
FLMs into the femoral vein (syringe pump) were begun at
time zero to achieve a steady state [FLM]circ equal to
4.2 ± 10^9/mm^3. The concentration of adherent FLMs
reached a steady level of 14 spheres/100 μm within 10
min and remained constant until fMLP superfusion of
the tissue was begun at 20 min after the start of
infusion. During the next 20 min, FLMs rose to a
maximal level of 130 spheres/100 μm. WBCs achieved
maximal adhesion within 10 min of onset of fMLP
superfusion.

The influence of the circulating concentration of
FLMs on the rate of adhesion to the endothelium was
explored, as shown in Fig. 3. Spontaneous (control)
adhesion of FLMs reached asymptotic levels with time
of infusion that were dependent on sphere concentra-
tion (Fig. 3A). The asymptotic level attained after ini-
tiation of superfusion with fMLP also increased with
sphere concentration (Fig. 3B). For both control and stimulated adhesion the time to reach maximal sphere accumulation was not strongly dependent on [FLM]_{circ}. Similarly, the stimulated increase in WBC adhesion was not significantly affected by the presence of all concentrations of FLMs (Fig. 3C). (The spontaneous adhesion of WBCs during control conditions was minimal because of a lack of tissue damage or a chemotactic agent and hence is not shown.)

Maximum Adhesion

The maximum adhesion of 1a29-FLMs and WBCs asymptotically attained with time is summarized in Fig. 4 for control and fMLP conditions, where the abscissa refers to the circulating sphere concentration, [FLM]_{circ}. For the 1a29-FLMs, under control conditions (spontaneous adhesion) their accumulation increased almost linearly with [FLM]_{circ} (Fig. 4A). However, maximal sphere adhesion rose asymptotically, reaching a maximum (150 per 100 mM) at 8–11 × 10^6 spheres/mm^3. In contrast, the maximal levels of WBC adhesion, during either spontaneous (control) or stimulated (fMLP) adhesion, was invariant with [FLM]_{circ} (Fig. 4B). A slight but insignificant decline in WBC adhesion was observed at a sphere concentration of 11 × 10^6/mm^3.

Rate of FLM Adhesion

The initial rate of adhesion of FLMs and WBCs for each [FLM]_{circ} was determined by fitting the number of adhesion events with a first-order exponential of the form \( N = A(1 - e^{-Bt}) \), where \( N \) is the number of adhesions/100 \( \mu \)m at time \( t \). Representative fits of these data are shown in Fig. 5, A–C, for [FLM]_{circ} of 10.87 × 10^6/mm^3. The initial rate of adhesion \( (dN/dt) \) was calculated as the product \( A \cdot B \) and is shown as a function of [FLM]_{circ} in Fig. 5, D–F. The initial rate of spontaneous 1a29-FLM adhesion (Fig. 5D) was significantly dependent on [FLM]_{circ} as determined by linear regression \( (P < 0.026) \), thus signifying the enhanced convective and diffusive transport of FLMs to the endothelium with increasing sphere concentration. The rates of fMLP-stimulated 1a29-FLM (Fig. 5E) adhesion were independent of [FLM]_{circ} \( (P = 0.215) \), thus suggesting that FLM binding was affected more by the
availability of ICAM-1 than by the availability of spheres. The invariance of the rate of fMLP-stimulated WBC adhesion with FLM concentration (Fig. 5; \( P = 0.727 \)) suggests that the presence of the spheres did not adversely affect WBC-EC adhesion by competing for binding sites.

**Micropipette Infusion Experiments**

To explore the basis for the more rapid accumulation of 1a29-FLMs compared with WBCs in response to fMLP stimulation, FLMs were infused directly into venules with micropipettes before and after removal of the glycocalyx with heparinase. The micropipettes were filled with concentrations similar in magnitude to those established by systemic infusion, i.e., \([\text{FLM}]_{\text{circ}}\) equal to 2.42, 8.46, and 10.87 \( \times 10^6/\text{mm}^3 \). Comparison of the systemic and micropipette infusions at identical \([\text{FLM}]_{\text{circ}}\) yielded statistically similar rates of accumulation and levels of 1a29-FLM adhesion (data not shown). Two protocols were used for the micropipette experiments. The first protocol involved a control period (20 min), followed by fMLP superfusion (10\(^{-7}\) M, 20 min), and finally heparinase infusion (1 U/ml, 10 min) followed by a measurement period (20 min). The second protocol involved a control period (20 min) followed by a heparinase infusion (1 U/ml, 10 min) and then fMLP superfusion (10\(^{-7}\) M, 20 min). The infusion flow rate of the heparinase was matched to that of the cannulated vessel.

Average values of \( V_{RBC}, D \), and wall shear rate for all periods of data acquisition (control and fMLP and heparinase protocols) are summarized in Table 1. No significant differences between hemodynamic parameters were apparent in the 85 venules studied.

**Heparinase infusion followed by fMLP suffusion.** Micropipette infusion of heparinase after a control period

![Fig. 3. Transient adhesion of FLMs under control conditions (A), FLMs after superfusion with 10\(^{-7}\) M fMLP (B), and WBCs after superfusion with fMLP (C). Shown are curves for the indicated circulating sphere concentrations (10^6/mm^3). Each curve is the average of \( n \) venules indicated. Standard deviations are omitted for clarity.](http://ajpheart.physiology.org/)

![Fig. 4. A: maximum number of FLMs adhered per 100-\( \mu \text{m} \) venule length, under control conditions and after superfusion of the tissue with fMLP, as a function of the circulating concentration of FLMs (\([\text{FLM}]_{\text{circ}}\)). The maximum adhesion was determined as the asymptotic value reached after 20 min, as depicted in Fig. 3. B: corresponding maximum amount of WBC adhesion per 100 \( \mu \text{m} \) vs. \([\text{FLM}]_{\text{circ}}\) during control and suffusion with fMLP (10\(^{-7}\) M). All data are shown as means \( \pm \) SD for the indicated number of venules (\( n \)).](http://ajpheart.physiology.org/)
of 1α29-FLM adhesion significantly increased 1α29-FLM adhesion ($P < 0.001$) to a maximum value that was independent ($P = 0.88$) of [FLM] circ (Fig. 6). The superfusion of fMLP 20 min after perfusion with heparinase did not cause a significant ($P = 0.94$) increase in FLM adhesion for any [FLM] circ. Similarly, the maximum adhesion of the 1α29-FLMs after fMLP superfusion was independent of [FLM] circ ($P = 0.74$).

The fraction of the free stream WBC flux that rolled along the venule wall, $F_{WBC}$ (Fig. 7A), decreased significantly ($P < 0.03$) from control values after heparinase treatment. After fMLP superfusion was started, $F_{WBC}$ remained unchanged. All changes in $F_{WBC}$ were independent of [FLM] circ. WBC firm adhesion (Fig. 7B) remained unchanged ($P = 0.48$) throughout the heparinase infusion and fMLP superfusion periods. The absence of significant changes in $V_{WBC}$ (Fig. 7C and Table 1) suggests that alterations in flow or wall shear rate did not contribute to the results.

**fMLP superfusion followed by heparinase infusion.** Direct micropipette infusion of 1α29-FLM under control conditions followed by fMLP superfusion (Fig. 8) resulted in FLM adhesion levels similar to those attained by the systemic infusion technique (Fig. 4A). Maximal FLM adhesion 20 min after initiation of fMLP superfusion was dependent on [FLM] circ and increased from 100 to 150 spheres/100 µm as [FLM] circ was increased from 2.42 to $10.87 \times 10^6$/mm³. The infusion of 1α29-FLM was temporarily stopped (by changing the pipette) while heparinase was infused. After heparinase infusion, the 1α29-FLM infusion was restarted and 1α29-FLM adhesion increased significantly ($P < 0.05$) to a similar maximum value of 180 spheres/100 µm for all [FLM] circ, which was independent of [FLM] circ ($P = 0.89$).

As shown in Fig. 9A, fMLP superfusion after the control period resulted in a significant 50% decrease in

### Table 1. Hemodynamic parameters for postcapillary venules

<table>
<thead>
<tr>
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<th>Control</th>
<th>fMLP</th>
<th>Heparinase</th>
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<tr>
<td></td>
<td>Vessels first superfused with fMLP, then infused with heparinase</td>
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</tr>
<tr>
<td>No. of venules</td>
<td>70</td>
<td>81</td>
<td>70</td>
</tr>
<tr>
<td>Diameter, µm</td>
<td>39.5 ± 8.1</td>
<td>39.3 ± 10.3</td>
<td>36.7 ± 10.9</td>
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<td>$V_{BEC}$, mm/s</td>
<td>2.68 ± 0.11</td>
<td>2.66 ± 0.50</td>
<td>2.42 ± 0.13</td>
</tr>
<tr>
<td>Shear rate, s⁻¹</td>
<td>512.6 ± 130.0</td>
<td>512.1 ± 166.8</td>
<td>497.1 ± 59.6</td>
</tr>
<tr>
<td></td>
<td>Vessels first infused with heparinase, then superfused with fMLP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of venules</td>
<td>70</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Diameter, µm</td>
<td>38.6 ± 12.1</td>
<td>39.2 ± 8.9</td>
<td>37.2 ± 10.2</td>
</tr>
<tr>
<td>$V_{BEC}$, mm/s</td>
<td>2.38 ± 0.25</td>
<td>2.53 ± 0.17</td>
<td>2.33 ± 0.34</td>
</tr>
<tr>
<td>Shear rate, s⁻¹</td>
<td>518.0 ± 177.8</td>
<td>495.8 ± 157.4</td>
<td>506.9 ± 139.6</td>
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Values are means ± SD of parameters measured in the micropipette perfusion protocols during the indicated treatment periods. FMLP, N-formylmethionyl-leucyl-phenylalanine; $V_{BEC}$, centerline red blood cell velocity. No significant differences were apparent among the 3 treatments.
F\text{WBC (P < 0.03)}, which was independent of [FLM]_{circ} (P = 0.74). F\text{WBC remained significantly lower (P = 0.045) than control values after heparinase infusion and did not change significantly from the post-fMLP values. These trends were independent of [FLM]_{circ}. In contrast, firm adhesion of WBCs (Fig. 9B) increased significantly (P < 0.001) from control values after fMLP superfusion and was independent (P = 0.96) of [FLM]_{circ}. After heparinase infusion WBC adhesion decreased significantly (P < 0.001) from the post-fMLP values and was independent (P = 0.82) of [FLM]_{circ}. These results do not appear to be influenced by variations in V_{RBC} or wall shear rate, as evidenced by the insignificant variations in V_{RBC} and wall shear rate indicated in Fig. 9C and Table 1.

**DISCUSSION**

It is well established that topical application of chemotactic agents to exteriorized microvascular preparations results in a rapid accumulation of adherent WBCs in postcapillary venules. However, it is not clear how much of this response may be attributed to WBC or EC activation. For example, topical application of fMLP gives rise to a sevenfold increase in adhesion within 30 s, to increase adhesion from 1 to 7 WBCs per 100-\mu m length of postcapillary venules, and within 3 min as many as 12 WBCs adhere per 100 \mu m (11). This level of WBC-EC adhesion produces a twofold increase in the resistance to flow within postcapillary venules.

The rapid increase of 1a29-coated microspheres (FLMs) demonstrated in Fig. 2 in response to topically applied fMLP is suggestive of a dominant EC component. Given that the response time is much shorter than that required for protein synthesis and upregulation of ICAM-1 on the EC surface (7), it is plausible that constitutive levels of ICAM-1, although fairly low, may be shielded from forming adhesive contact with FLMs or WBCs. Visual inspection of the deposition of FLMs on the EC during stimulation reveals a patchy pattern.

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**Fig. 6.** Adhesion of FLMs during micropipette infusion, averaged for 15 venules for each of the indicated [FLM]_{circ}. After a 20-min control period, the infusion solution was changed to heparinase (1 U/ml), and the venules were perfused for 10 min at a rate of 4 \times 10^{-4} \text{ mm/s}. Infusion of FLMs was then resumed and continued for an additional 20 min, after which the tissue was suffused with 10^{-7} M fMLP. All data are shown as means \pm SD.

**Fig. 7.** Variations of the fractional flux of WBCs rolling along the venular wall (F_{WBC}; A), number of WBCs adhering per 100-\mu m venule length (B), and V_{RBC} (C) corresponding to the protocols described in Fig. 6 for micropipette perfusion of individual venules. The concentration of FLMs (10^6/mm^3) is shown as in Fig. 6. Periodic samplings of venular V_{RBC} reflect an absence of flow variations that could affect rolling and adhesion. Heparinase caused a significant drop in WBC rolling flux, which was not affected by the topical application of fMLP.
distribution along the venular length, similar in sparseness to the adhesion of WBCs (Fig. 1). In contrast, studies of the distribution and binding of fluoresceinated 1a29 to the venular EC revealed a much more homogeneous deposition of MAb (13). With the use of confocal microscopy on fixed tissues, these studies suggest that although the constitutive expression of ICAM-1 was markedly heterogeneous throughout the hierarchy of arterioles, capillaries, and venules, within individual venules MAb binding to ICAM-1 was uniformly distributed over long sections of venules. Thus it appears that a barrier limits the binding of FLMs to the EC, and it is hypothesized here that the glycocalyx may shield ICAM-1 from binding by FLMs.

Evidence suggests that ICAM-1 may extend only 18.7 nm above the surface of the endothelium (25), whereas various constituents of the glycocalyx may consist of much larger and longer molecules. Most common macromolecular components of the glycocalyx are carbohydrates and glycoproteins such as glycosaminoglycans (GAGs) and glycolipids (20). The primary GAGs, heparan sulfate and chondroitin sulfate, are attached to large transmembrane proteins to form the proteoglycans (syndecans). The ICAM-1 molecule (76–114 kDa) is dwarfed in size compared with the syndecan core protein (~69 kDa) plus attached heparan sulfate GAGs (41.5 and 60 kDa). Typically, syndecans carry multiple heparan sulfate molecules and have a total mass ranging from 160 to 400 kDa (14), which, on the basis of molecular weight, overshadows ICAM-1.

In vitro attempts to measure the thickness of the glycocalyx have been dominated by histochemical methods that have revealed a range from 20 to 100 nm (19). The presence of a functionally larger layer thickness has been suggested by in vivo observations of the increase in capillary hematocrit after removal of the glycocalyx with heparinase (5). These studies suggest that the glycocalyx may extend on the order of 1 μm into the lumen. Observations in vivo with membrane-bound fluorescent dyes and fluorescently labeled dextrans in plasma (28) have suggested a functional thickness of the glycocalyx ranging from 400 to 500 nm.
vivo studies of the permeation of the glyocalyx with anionic tracer molecules reveal a dependence of the penetration of the glyocalyx on molecular size, charge, and structure (29). Thus it is plausible that the presence of a 0.1-μm diameter polystyrene sphere attached to the 1a29 MAb limits its penetration into the glyocalyx and subsequent binding to ICAM-1.

The use of fluorescently coated microspheres in vivo has the additional advantage of permitting rapid visualization of an extremely small number of binding sites. The dense loading of each sphere with a large number of fluorophores renders their presence and position easily detectable within the focal plane and along the vertical optical axis without the necessity of resorting to confocal microscopy. The 0.1-μm-diameter spheres appear to be small enough that the hydrodynamic drag force that tends to remove each sphere from the endothelium is an order of magnitude below that of drag forces acting on particles the size of a leukocyte (23). The density of labeling of MAb on the surface of the sphere used here (88 1a29 molecules/sphere) amounts to ~2,800 1a29 molecules/μm². This is far greater than estimates of the surface density of adhesive bonds derived from in vivo measurements of the adhesive force between WBCs and ECs in postcapillary venules (12). As shown in that study, the contact zone between WBCs and ECs may possess on the order of 30 bonds per WBC, and on the basis of the typical contact areas between the two cells a bond density on the order of 2 bonds/μm² may be present. Thus the adhesion of 1a29-coated FLMs to the EC does not appear to be dependent on prevailing levels of wall shear stresses and reflects mainly the availability of ICAM-1 binding sites. Flow-dependent effects were generally precluded by the maintenance of similar levels of wall shear rate for all treatments (Table 1).

The baseline level of FLM adhesion before application of fMLP (Fig. 2) or infusion of heparinase (Fig. 6) appears to be a nonlinear function of the concentration of circulating spheres (Fig. 4A) as well as the availability of ICAM-1 binding sites. In general, the accumulation of FLMs on the EC surface will depend on the equilibrium between convection of spheres to potential binding sites, the kinetics of bond formation and disruption, and the levels of hydrodynamic forces tending to remove the FLMs from the EC. In light of the trends in Fig. 4A, it appears that for sphere concentrations of 8 and 11 × 10⁶/mm² the convection of spheres to the EC does not affect the results.

The longer time to achieve an asymptotic value for lesser FLM concentrations (Fig. 3A) may also reflect the rate of sphere uptake by other sites during systemic infusion. It has been shown that large regional differences in constitutive and induced ICAM-1 expression vary widely among organs (17). For example, as shown in that study, splanchnic beds have a constitutive level of ICAM-1 that is 1/50th of that of the lung. Comparison of the present baseline level of sphere adhesion (~50 spheres/100 μm; Fig. 4A) with similar measures of ICAM-1 expression in lung (7) reveals disparities that may reflect organ-specific and topographical differences within a given network. In that study, by studying the accumulation of avidin-labeled microspheres (0.28-μm diameter) to biotin-labeled MAb to ICAM-1, a constitutive level of two spheres per 175,000 μm² was found. Normalization of these values to the surface area of a typical 100-μm-long venular section in the present study (10,000 μm²) yields an equivalent level of binding equal to 0.02 spheres/100 μm, which is 1/2,500th of the baseline level observed here. This disparity may reflect differences in sensitivity of the methods employed, the substantially greater density of ICAM-1 in the small postcapillary venules of the mesentery, and/or the greater exclusion of the larger microspheres by the glyocalyx.

Studies of the upregulation of ICAM-1 in pulmonary microvessels (7) reveal a 1- to 4-h time after TNF-α challenge to produce a threefold upregulation of ICAM-1, with one-third of its maximal expression occurring at 1 h and peak expression at 4 h after stimulation. Thus the threefold increase in FLM adhesion observed in the present study after 20 min of fMLP stimulation (Fig. 8) suggests that ICAM-1 rapidly becomes more accessible to FLMs or WBCs after exposure to fMLP.

It is conceivable that the enhanced accessibility of ICAM-1 results from shedding of the glyocalyx after EC activation. To explore this hypothesis, FLM and WBC adhesion were examined before and after perfusion of individual venules with heparinase. It is evident that maximal FLM adhesion was attained after removal of the glyocalyx with heparinase and that subsequent stimulation with fMLP did not result in an incremental increase (Fig. 6). The results shown in Fig. 8 for FLMs suggest that fMLP adhesion alone did not saturate all potential binding sites on the EC for FLMs, because subsequent infusion of heparinase produced an additional increment of FLM adhesion. In both protocols, the rolling flux of WBCs was on the order of 40% after the control period.

The decline in F_WBC after fMLP superfusion (Fig. 9B) has been observed previously (12) and may reflect WBC depletion of the rolling stream as WBCs accumulate along the EC with the stimulated adhesion. The number of adhered WBCs at any instant of time represents a balance of WBC adhesion and removal rates. The fall in WBC adhesion after heparinase treatment (Fig. 9B) and the decreased flux in response to heparinase alone (Fig. 7A) most likely reflect a diminished ability to support selectin-mediated rolling resulting from removal of the glyocalyx and associated E- or P-selectins. Because WBCs cannot roll along the EC, adhesion cannot be enhanced with fMLP (Fig. 7B). Hence, it is thus possible that fMLP activation of the EC results in a shedding of the glyocalyx that is comparable to its removal with heparinase. This behavior is consistent with in vitro observations that heparinase inhibited 80% of L-selectin-mediated monocyte attachment to TNF-α-activated aortic endothelium (9). Similarly, it has been shown that P-selectin must extend a minimum distance from the plasma membrane to support WBC rolling (18).
It is thus evident from the present studies that the glycocalyx presents a physical barrier between WBCs and ECs that may play an important role in mediating the inflammatory response. As a means of elucidating its role, the present study represents a first step that may lead to other more direct biochemical analyses of molecular alterations in the glycocalyx with EC activation. It should be noted that the precise mechanism by which fMLP acts directly to activate the endothelium or promote exposure of ICAM-1 on its surface warrants further study. It is conceivable that fMLP activation of other cells in the tissue, e.g., mast cells, may play a role. However, because the initial adhesion response is so rapid and the spatial distribution of mast cells in mesentery low and distant from the EC, this pathway is unlikely.

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