Integrin–Matrix Interactions in the Cerebral Microvasculature

Gregory J. del Zoppo, Richard Milner

Abstract—The integrity of all organ systems requires faithful interaction between its component cells and the extracellular matrix (ECM). In the central nervous system (CNS), matrix adhesion receptors are uniquely expressed by the cells comprising the microvascular compartment, and by neurons and their supporting glial cells. Cells within the cerebral microvasculature express both the integrin and dystroglycan families of matrix adhesion receptors. However, the functional significance of these receptors is only now being explored. Capillaries of the cerebral microvasculature consist of the luminal endothelium, which is separated from circumferential astrocyte end-feet by the intervening ECM of the basal lamina. Endothelial cells and astrocytes cooperate to generate and maintain the basal lamina and the unique barrier functions of the endothelium. Integrons and the dystroglycan complex are found on the matrix-proximate faces of both endothelial cells and astrocyte end-feet. Pericytes rest against the basal lamina. In the extravascular compartment, select integrins are expressed on neurons, microglial cells, and oligodendroglia. Significant alterations in both cellular adhesion receptors and their ligands occur under the conditions of focal cerebral ischemia, multiple sclerosis (MS) and the modeled condition experimental autoimmune encephalomyelitis (EAE), certain tumors of the CNS, and arteriovenous malformations (AVMs). The changes in matrix adhesion receptor expression in these conditions support their functional significance in the normal state. We propose that matrix adhesion receptors are essential for the maintenance of the integrity of the blood–brain permeability barrier, and that modulation of these receptors contribute to alterations in the barrier during brain injury. This review examines current information about cell adhesion receptor expression within the cerebral microvasculature and surrounding tissue, and their potential roles during the vascular responses to local injury. (Arterioscler Thromb Vasc Biol. 2006;26:1966-1975.)

Key Words: blood–brain barrier • cerebral microvasculature • dystroglycan • integrins • matrix adhesion receptors

The cerebral microvasculature is unique in that while serving as a conduit for supplying blood-to-brain structures, it is also completely incorporated within the neuropil, allowing direct interactions with glia and neurons. The cerebral microvasculature is also functionally dynamic. It maintains and with states of arousal and neuronal activation increases local and regional blood flow to provide cellular nutritional support.1–4 Both local and distant control of cerebral blood flow during activation results from neurovascular coupling via astrocytes, and from direct innervation.1,2 The close proximity between the endothelium and astrocyte end-feet of intact cerebral capillaries also implies potential communication between the cells across the basal lamina.

Pial and cortical penetrating arteries consist of an endothelial cell layer, the basal lamina (derived from the extracellular matrix [ECM]), a myointima with smooth muscle cells encased in the matrix, and an adventitia.5 Arising from the leptomeninges, the adventitia of the cortical penetrating arteries is an extension of the subarachnoid space which forms the Virchow-Robbins space until it disappears into the glia limitans, the abluminal boundary formed by the astrocyte end-feet in small-caliber microvessels.5–7 In the cortical gray matter, the microvasculature consists of hierarchical arrays descending from pial penetrating arteries.8–10 In contrast, in the gray matter of the corpus striatum neurons are arranged in a more-or-less consistent and orderly fashion in relation to their adjacent microvessel supply.11 These arrangements derive from laminin-directed migration of both neurons and microvessel elements during development of the central nervous system (CNS).12–14 Capillaries comprise ≥60% of the cerebral microvasculature, and are an integral part of the neuropil. Within cerebral capillaries the matrix-containing basal lamina separates the specialized endothelium from astrocyte foot processes.5,15 Astrocytes participate in both the capillary ultrastructure and in communication with nearby neurons. Communication among astrocytes follows from their syncytial arrangement
and occurs via Ca\(^{2+}\) channels. Neuronal stimulation can initiate microvascular and endothelial cell responses via these glial elements. Nedergaard has shown that neuronal function can also be modulated by astrocyte activation, and that astrocytes can signal.

In addition to these cellular components of cerebral capillaries, recent evidence suggests the importance of pericytes and microglia to maturation of endothelial cell contacts and to the responses of the neurovascular unit to ischemia. Pericytes are found in the basal lamina matrix on the luminal aspect of astrocyte end-feet.

**Endothelial Transport Properties**

Cerebral capillaries strictly limit transport of solutes, proteins, and chemical agents in the circulation into the neuropil. In particular, activated proteases (eg, thrombin) from the plasma compartment toxic to neurons and supporting cells are prevented from reaching the extravascular space. The capillary endothelium is the primary interface for regulation of the exchange of amino acids, transport of ions via the Na\(^+/K^+\)/Cl\(^-\) co-transporter, the Na\(^+/H^+\) exchanger, the inward rectifying K\(^+\) channel, and other ports, the entry of glucose via its transporters, and the transport of fatty acids and lysophosphatidylcholine from the plasma. These ports regulate the ionic milieu of the astrocyte end-feet, and the energy supply for the neuropil.

**Specialization of the Microvasculature**

Regional specialization of cerebral microvascular endothelial cell function exists along the microvessel axis. Spatz et al have shown that under normal conditions glucose and amino acid transporter expression varies with the microvessel diameter. During local inflammation, adhesion receptors for leukocyte adhesion are expressed predominantly by the post-capillary venule endothelium. In view of both regional and individual specialization of neurons, local subspecialization of the neuron-microvessel relationship in cerebral microvascular beds seems possible, although as yet unproven. Another reflection of this specialization is the variation in expression of adhesion receptor types and their matrix ligands in the cerebral microvasculature.

**The Cerebral Microvascular Permeability Barrier**

The functional barrier properties of cerebral microvessels are represented by 2 structures: (1) the cohesive and resistance properties of the endothelial cells, involving the inter-endothelial tight junction proteins zonula occludens-1 (ZO-1), claudin-5, occludins, and junctional adhesion molecules; and, the adherens complex, E-cadherin; and (2) the intact basal lamina (Figure 1). Both the endothelial cell permeability barrier and the basal lamina matrix derive from cooperation between the endothelium and astrocytes, which together constitute the blood–brain barrier. The integrins and dystroglycan constitute 2 well-characterized families of the cellular–ECM adhesion receptors associated with the microvasculature in the CNS.

**Matrix Adhesion Receptors**

The integrins and dystroglycan constitute 2 well-characterized families of the cellular–ECM adhesion receptors associated with the microvasculature in the CNS.

**Integrins**

Integrins are cell surface transmembrane, noncovalently-linked αβ heterodimers that recognize specific matrix ligands. Functionally, integrins can regulate cell behavior by:
Table 1. Phenotypes of Integrin Subunit Deletions in Mice

<table>
<thead>
<tr>
<th>Integrin Subunit</th>
<th>Viability</th>
<th>Fertility</th>
<th>Phenotype</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha_1)</td>
<td>+</td>
<td>+</td>
<td>Defects in bone healing and reduced tumor</td>
<td>123</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>angiogenesis</td>
<td></td>
</tr>
<tr>
<td>(\alpha_2)</td>
<td>+</td>
<td>+</td>
<td>Reduced branching morphogenesis and platelet</td>
<td>124</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>adhesion</td>
<td></td>
</tr>
<tr>
<td>(\alpha_3)</td>
<td>Perinatal lethal</td>
<td>+</td>
<td>Kidney, lung, and skin defects</td>
<td>62</td>
</tr>
<tr>
<td>(\alpha_4)</td>
<td>Embryonic lethal</td>
<td>-</td>
<td>Placental and heart defects</td>
<td>58</td>
</tr>
<tr>
<td>(\alpha_5)</td>
<td>Embryonic lethal</td>
<td>-</td>
<td>Mesodermal and vascular defects</td>
<td>59</td>
</tr>
<tr>
<td>(\alpha_6)</td>
<td>Perinatal lethal</td>
<td>+</td>
<td>Epidermal detachment, \textit{defect in neurogenesis}</td>
<td>63</td>
</tr>
<tr>
<td>(\alpha_7)</td>
<td>+</td>
<td>+</td>
<td>Muscular dystrophy</td>
<td>125</td>
</tr>
<tr>
<td>(\alpha_8)</td>
<td>Perinatal lethal</td>
<td>+</td>
<td>Kidney defect</td>
<td>60</td>
</tr>
<tr>
<td>(\alpha_9)</td>
<td>Perinatal lethal</td>
<td>+</td>
<td>Chylothorax (defect in lymphatic drainage)</td>
<td>126</td>
</tr>
<tr>
<td>(\beta_1)</td>
<td>Embryonic and perinatal lethal</td>
<td>+</td>
<td>Cerebral hemorrhage</td>
<td>64</td>
</tr>
<tr>
<td>(\beta_2)</td>
<td>Embryonic lethal</td>
<td>-</td>
<td>Fails to gastrulate</td>
<td>61, 64</td>
</tr>
<tr>
<td>(\beta_3)</td>
<td>+</td>
<td>+</td>
<td>Leukocyte adhesion deficiency</td>
<td>127</td>
</tr>
<tr>
<td>(\beta_4)</td>
<td>+</td>
<td>+</td>
<td>Platelet defect</td>
<td>128</td>
</tr>
<tr>
<td>(\beta_5)</td>
<td>Perinatal lethal</td>
<td>+</td>
<td>Epidermal detachment</td>
<td>65</td>
</tr>
<tr>
<td>(\beta_6)</td>
<td>+</td>
<td>+</td>
<td>Accelerated age-related blindness</td>
<td>129</td>
</tr>
<tr>
<td>(\beta_7)</td>
<td>+</td>
<td>+</td>
<td>Inflammation in skin and lungs</td>
<td>130</td>
</tr>
<tr>
<td>(\beta_6)</td>
<td>Embryonic and perinatal lethal</td>
<td>+</td>
<td>Gut-associated lymphocyte defects</td>
<td>131</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cerebral hemorrhage</td>
<td>66</td>
</tr>
</tbody>
</table>

Dystroglycan

Dystroglycan is a single \(\alpha\beta\) heterodimeric transmembrane receptor, distinct from integrins, that forms a physical link between the extracellular matrix and the cell cytoskeleton. The \(\alpha\) subunit is formed from proteolytic cleavage of a single precursor, and interacts noncovalently with the 43-kDa transmembrane \(\beta\) subunit to form the active receptor.46–47 \(\alpha\)-dystroglycan, the 120- to 190-kDa glycosylated extracellular subunit, binds to the ECM proteins laminin (the laminin-\(\alpha_2\) chain), perlecan (heparin sulfate proteoglycan [HSPG]), and agrin.48,49 The intracellular carboxy-terminus of \(\beta\)-dystroglycan binds to the cytoskeletal proteins dystrophin and utrophin.50,51 Expression of \(\alpha\beta\)-dystroglycan in the cerebral microvasculature is associated with both endothelial cells and astrocytes.49,52,53 The dystroglycan complex shares laminin as the primary matrix ligand with a number of integrin receptors, including \(\alpha_1\beta_1\), \(\alpha_2\beta_1\), \(\alpha_3\beta_1\), and \(\alpha_4\beta_1\), which are also expressed in the CNS microvasculature.54–57

Roles of Integrin Receptors in the CNS as Defined by Integrin Null Mice

Because the absence of integrin subunit \(\alpha_4\), \(\alpha_5\), \(\alpha_6\), or \(\beta_1\) expression results in embryonic lethality in murine knockout constructs (Table 1),58–61 it has not been established whether their functions are required for maintaining blood–brain barrier integrity. Deletions of the integrin subunits \(\alpha_1\), \(\alpha_6\), \(\alpha_8\), \(\beta_1\), or \(\beta_8\) are lethal in the perinatal period in mice.62–66 Significantly, deletions of the integrin subunits \(\alpha_4\), \(\alpha_5\), and \(\beta_8\) demonstrate a clear CNS phenotype.64,66,67

\(\alpha_4\) Integrin

The premature death of \(\alpha_4\) integrin null mice is caused by defective attachment of the epidermis to the matrix of the underlying basement membrane (reminiscent of the disorders junctional epidermolysis bullosa and bullous pemphigoid in humans).63 Mice lacking the integrin \(\alpha_4\) subunit also show defective neuronal migration in the CNS. Neurons migrate beyond their normal position resulting in disordered layering of the cerebral cortex and neuronal ectopia on the outer surface of the cortex.67 A similar phenotype is generated by deletion within the laminin \(\gamma_1\) chain gene and the gene of the ECM protein reelin,68,69 demonstrating that laminin \(\alpha_4\beta_1\) signaling is required for the establishment of neuronal patterning during cerebral development. The impact on cerebrovascular development has not been investigated.

\(\alpha_6\) or \(\beta_8\) Integrins

Within the CNS, the endothelium or microvascular structures associated with the endothelium depend on integrin \(\alpha_6\beta_1\) in a way that blood vessels outside the CNS do not.70 Mice which lack the \(\alpha_6\) or \(\beta_8\) integrin subunits suffer cerebral hemorrhage, and do not survive past the perinatal period.64,66 Cerebral vessels in \(\alpha_6\) or \(\beta_8\) null constructs dilate at an early developmental stage resulting in a leaky vasculature. This defect has been attributed to failure of proper adhesive interactions among the neuroepithelial cells, astrocytes, and endothelial cells during cerebrovascular development. Conditional
knockout preparations which specifically remove αι integrins from either endothelial cells or astrocytes have demonstrated that integrin αιβι expressed by astrocytes is important for the adhesive interaction to take place.71,72 Recent work has suggested that astrocyte αιβι integrin may activate transforming growth factor-β and thereby stabilize the endothelium, such that in the absence of this integrin, the microvasculature is more prone to hemorrhage.73

βι Integrins
The role of βι integrins in neurons and glia has been evaluated using cre-lox technology. Such cell-selective knockouts produce a phenotype similar to deletions of the αι integrin, γ-laminin, and reelin genes.63,68,69 Integrin βι−/− neurons adhere to and migrate along radial glia normally, but result in a disordered neuronal layering of the cerebral cortex.74 Furthermore, glial end-feet fail to make proper connections to the meningeal basement membrane, disordering the marginal zone of the developing cerebral cortex and resulting in aberrant cortical organization. Hence, while βι integrins are not required for neuronal adhesion, survival, or migration, they participate in glial-matrix interactions at the meninges, and are required for the proper establishment of the marginal zone in the developing cerebral cortex.

To date, the consequences of conditional knockout of the integrin βι subunit on the cerebral vasculature are not known. The loss of βι integrin expression on both endothelial cells and astrocytes after focal cerebral ischemia accompanies structural alterations in the microvasculature.75 This suggests essential roles for βι integrins within the microvasculature.

Regulation of Integrin Expression and Function During CNS Development
Integrin function is regulated by the level of cell surface expression and by the level of integrin activation. For example, in the developing CNS, retinal ganglion axons adhere to and extend on laminin until they reach the tectum, where they detach from laminin.76 This is caused by both decrease in the axonal surface expression of integrin αιβι and loss of the active conformation of the βι integrins still expressed on the cell surface of retinal ganglion cells.77,78 Another form of developmental integrin regulation is exemplified by oligodendroglial cells which change the βι-subunit partners of αι integrins from αιβι to αιβι3 during terminal differentiation.79

Cerebral blood vessel maturation is associated with marked up-regulation of βι integrin expression during CNS development,80 which coincides with a switch in endothelial cell βι integrin expression. In the postnatal angiogenic period cerebral endothelial cells express the fibronectin receptors αιβι3 and αιβι4, but after cessation of angiogenesis, switch to the laminin receptors αιβι and αιβι3. This “integrin switch” coincides with a concomitant change in the endothelial cell–matrix ligands from fibronectin to laminin. Taken together, this suggests an instructive role for βι integrins during angiogenesis in the CNS.

Adhesion Receptor Expression in the Adult Brain
The constitutive high level expression of select integrins and dystroglycan within the cerebral capillaries in mature adult brain suggest active links of endothelial cells and astrocyte end-feet to the intervening basal lamina matrix (Table 2).32,81–83

Endothelial Cells
βι Integrins
Haring et al characterized microvascular integrin subunit expression in the normal primate striatum and cortex gray matter,35 in part confirming other reports of vascular integrin expression in human brain (Table 2).81–83 Integrin subunits αι, and αι are distributed throughout the normal cerebral microvasculature in a pattern identical to subunit βι,81 suggesting the common expression of integrins αιβι and αιβι throughout the cerebrovascular tree in all mammalian species.82 Their expression parallels that of the βι-matrix ligands laminin, collagen IV, and fibronectin. The integrin αι subunit is expressed on a subset of capillaries less frequently than αι or αι. The reasons for this differential expression are not known.32 McGeer et al and Paulus et al confirmed that integrin αι appears on the cerebral microvasculature, and Haring et al noted its expression by non-capillary microvessels exclusively in a pattern quite similar to subunits αι, αι, and βι.81,82 The expression of several known typical αι-subunit partners for the integrin βι on select capillary/microvessel subclasses might be explained by endothelial cell specialization along the microvascular axis.

Integrin αιβι
Integrin subunits αι and βι are roughly equally expressed on a very small proportion of resting non-capillary microvessels in comparison to the distribution of basal lamina matrix proteins.32,84 Integrin αιβι expression is significantly upregulated after the onset of focal ischemia.85

Glial Cells
βι Integrins
The observation of βι integrin expression on astrocytes is consistent in post-mortem human brain and rat brain.82,83 Both subunits αι and βι are found on astrocyte fibers surrounding select microvessels in the adult primate.32,86 In addition, murine primary astrocytes in culture express integrins αιβι, αιβι, αιβι1, and αιβι2.87,88 Function-blocking studies show that these integrins are functionally active adhesion receptors for laminin (αιβι1, αιβι2, and αιβι3) and fibronectin (αιβι3).88,89 Astrocytes in culture also express integrins αιβι1 and αιβι3 which, on a vitronectin substrate, promote astrocyte adhesion and migration, respectively.89

Integrin αιβι
Integrin αιβι is expressed on the astrocyte end-feet in a small proportion of normal capillaries and noncapillary microvessels (Table 2).32,86 The reasons for this restricted expression are so far unknown. A matrix ligand for integrin αιβι, laminin-5 is codistributed in the cerebral microvascular basal lamina with the major matrix constituents laminin-1, collagen type IV, and cellular fibronectin.80–82 Hemidesmosomes, which anchor epithelial cells to the cuticular basement membrane, contain the integrin αιβι4.90,91 and have been found in astrocyte end-feet at the vascular basal lamina interface of larger
In short, integrin α4β1 could play active roles in the attachment of astrocyte end-feet to the basal lamina of select microvessels for maintaining their close apposition to the endothelium.

Other Integrin Receptors

While α4 and α6 integrins are expressed during angiogenesis, they are developmentally downregulated after angiogenesis and are expressed by only a small proportion of noncapillary cerebral microvessels in the primate. But, subunit α5, and not α4, has been identified on adult human cerebral microvessels in one report.

Vascular Matrix-Adhesion Receptor Expression During Focal Cerebral Ischemia

The rather static ultrastructural features of the cerebral microvasculature belie considerable local reactivity. Experimental preparations demonstrate that within the core regions of ischemic injury the apparently stable microvasculature responds rapidly after occlusion of a brain-supplying artery. For instance, changes in microvessel integrin expression occur within 1 to 2 hours in the ischemic core, and are accompanied by detachment of astrocyte end-feet, local loss of permeability barrier integrity with edema accumulation, and the appearance of markers of angiogenesis (Table 2). The endothelial cell-associated leukocyte adhesion receptors P-selectin and intercellular adhesion molecule-1 also appear in this time frame, followed by the expression of E-selectin.

The changes seen in microvascular integrin expression accompany rapid local alterations in their matrix ligands within the basal lamina. Laminin-1, collagen type IV, and cellular fibronectin decrease to ∼60% of the baseline in the ischemic core by 24 hours following middle cerebral artery occlusion (MCAO). Within 2 hours there is significantly greater loss of the HSPG perlecan than laminin within the basal lamina, indicating the greater sensitivity of this integrin β1-ligand to focal ischemia. These events correlate with the simultaneous generation of the matrix proteases pro-matrix metalloproteinase (MMP)-2 (pro-MMP-2), pro-MMP-9, and their activators urokinase, membrane-type 1 (MT1)-MMP, and MT3-MMP on microvessels (and neurons) within the regions of injury. Cysteine protease activity, marked by the appearance of cathepsin L, corresponds to the loss of HSPG. Importantly, loss of the major basal lamina proteins are directly associated with extravasation of erythrocytes and hemorrhagic transformation.

Endothelial Cells

While the endothelium remains intact, glial end-feet are displaced from the basal lamina. By 2 hours after MCAO, endothelial cell β1-integrin expression by the endothelium is lost in 69±7% of microvessels within the ischemic core. This loss is sustained and does not recover despite restitution of flow. The mechanisms by which
ischemia diminishes microvessel β1 expression are not yet known. However, within the ischemic core, downregulation of microvessel-associated integrin β1 gene appears heterogeneous: confluent regions of increased β1 transcription on microvessels surround subregions with depressed β1 expression early after MCAO.75 The upregulation of β1 in the boundary between the ischemic core and the intermediately affected peripheral zone, and around subregions lacking expression, is consistent with the notion that the “ischemic penumbra” is initially interspersed among relatively unaffected tissue within the core.75 In time all β1 gene expression ceases as the injured subregions merge.

Within the ischemic core, the subunits α1, α5, and α6 are significantly depressed in parallel with the β1 subunit (Table 2, Figure 3),72 suggesting that all endothelial cell β1-integrin complexes are affected by ischemia. Endothelial cell α1β1 expression continues on microvessels which retain laminin within the intact basal lamina; the loss of this integrin generally precedes that of laminin.79 But, there is no evidence of endothelial cell detachment early after MCAO. The relationships of these changes to local flow conditions are not yet known.

**Integrin α1β1**

Capillary bud formation appears by 7 days after MCAO.99,100 However, it is not yet known what roles integrin α1β1 plays in cerebral angiogenesis. Tissue culture studies have shown that integrin α1β1 is expressed by cerebral endothelial cells,101 but not astrocytes.89 While α1β1 is not normally expressed by resting endothelial cells in vivo, it is induced during angiogenesis or in cell culture, and plays an important role in mediating brain capillary endothelial cell adhesion to fibronectin, thus promoting endothelial cell survival and proliferation.101 Focal ischemia stimulates the consistent and significant early expression of the integrin α1β1 on activated

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**Glial Cells**

**Integrin α1β1**

After the onset of focal ischemia, integrin α1β1 is rapidly lost from the astrocyte end-feet of select microvessels.86 This corresponds to the separation of astrocytes from the vascular matrix early after MCAO, and to the cell swelling and loss in cytoplasmic density, which accompanies astrocyte separation (Figure 2). These changes in ultrastructure and integrin α1β1 expression also imply fundamental alterations in the end-foot apparatus.

**Multiple Sclerosis and Experimental Autoimmune Encephalomyelitis**

Considerably less is known about the fate of matrix adhesion receptors in the development of lesions in multiple sclerosis (MS). Integrin α1β1 expression on microvascular endothelial cells is altered in MS (Table 2).103 During the active phase of MS, the expressions of the integrin β1 and α6 subunits are
decreased, but return to normal during the inactive recovery phase (Table 2). This indicates that loss of endothelial adhesion receptors coincides with increased barrier permeability during the active phase of MS, and implies that adhesion receptor function is necessary for maintenance of the blood–brain barrier.

In experimental autoimmune encephalomyelitis (EAE), an animal model of MS, the expressions of the integrin β₃ and α₄ subunits on astrocytes are increased.¹⁰⁶ This effect can be reproduced in vitro when primary astrocytes are treated with the pro-inflammatory cytokine tumor necrosis factor-α. This implies that cytokine expression could drive matrix receptor expression on microvascular cells (ie, astrocytes). In addition, a recent study described loss of dystroglycan from astrocyte end-feet during EAE.¹⁰⁷

**Targeting Integrin–Matrix Interactions as Potential Treatments**

To determine the roles of specific integrins in the CNS, function-blocking reagents including monoclonal antibodies and peptides, have been used. Because the importance of integrin-matrix interactions in the regulation of cerebral vascular permeability is only now being realized, specific function-blocking studies have not yet addressed the role of these adhesive events in the integrity of the blood–brain barrier. However, so far 2 nonbarrier integrin-mediated events have been examined in neurological disease: (1) leukocyte infiltration into the neuropil and (2) platelet activation during stroke.

Leukocytes enter the neuropil during the cellular inflammatory phases of MS and ischemic stroke.¹⁰⁸–¹¹¹ In murine EAE, α₄ integrins and to a lesser extent the β₃ integrins on leukocytes mediate their adhesion to the endothelium and transmigration.¹¹²,¹¹³ Based on promising data from animal studies, clinical trials have established that infusion of a humanized monoclonal antibody against the α₄ integrin subunit into patients with the relapsing–remitting form of MS, the expressions of the integrin β₄ and α₃ in ischemic and inflammatory (eg, MS), have largely ignored the roles of microvessel endothelial cell-matrix-astrocyte adhesion interactions, but mostly focus on interendothelial cell cohesion.

Three lines of evidence suggest that matrix adhesion receptors may play an important role in maintaining the permeability barrier of the brain. First, select integrins and dystroglycan are expressed at high levels specifically at the blood–brain barrier. Second, alterations in the expression of these receptors coincide with breakdown of the permeability barrier, leading to glial activation and neuronal injury. Third, studies of transgenic mice show that the absence of specific integrins leads to breakdown of the cerebral vasculature, supporting the notion that ECM receptors could participate in the maintenance of cerebrovascular integrity.

Based on those observations, we propose that the microvessel permeability barrier in the brain consists of both “horizontal” and “vertical” components. The tight junctions that form between adjacent endothelial cells have been viewed as the basis for the endothelial permeability barrier in mammalian brain. The tight junctions and the interendothelial adherens complexes together constitute the “horizontal” component. We wish to extend this model to include a vertical component, consisting of the matrix adhesion complexes formed between adhesion receptors on both endothelial cells and astrocytes, which anchor the cells to the intervening basal lamina of extracellular matrix. “Vertical” adhesion of the astrocyte foot processes by matrix receptors maintains the close proximity of the astrocyte portion of the microvascular compartment to the endothelium, and hence their contribution to endothelial cell barrier integrity. This proximity is necessary for the competence of the microvascular barrier and its unique resistance properties in the CNS. One important implication of this concept is that by altering vertical adhesion at the barrier interface new avenues of therapeutic potential could be devised.

**Adhesion Receptors and the Permeability Barrier**

Those observations suggest a need to examine CNS barrier function more carefully. Alterations in endothelial cell and astrocyte adhesion receptor expression within cerebral microvessels coincide with neuronal injury, glial activation, and breakdown of the blood–brain permeability barrier. Current views of blood–brain barrier integrity, altered during focal ischemia and inflammation (eg, MS), have largely ignored the roles of microvessel endothelial cell-matrix-astrocyte adhesion interactions, but mostly focus on interendothelial cell cohesion.

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**Disclosures**

None.
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