Effect of a Broad-Specificity Chemokine-Binding Protein on Brain Leukocyte Infiltration and Infarct Development

Seyoung Lee, BSc(Hons); Hannah X. Chu, BSc(Hons); Hyun Ah Kim, PhD; Nicola C. Real, BSc(Hons); Saeed Sharif, DVM, MSc; Stephen B. Fleming, PhD; Andrew A. Mercer, PhD; Lyn M. Wise, PhD; Grant R. Drummond, PhD; Christopher G. Sobey, PhD

Background and Purpose—Expression of numerous chemokine-related genes is increased in the brain after ischemic stroke. Here, we tested whether post-stroke administration of a chemokine-binding protein (CBP), derived from the parapoxvirus bovine papular stomatitis virus, might reduce infiltration of leukocytes into the brain and consequently limit infarct development.

Methods—The binding spectrum of the CBP was evaluated in chemokine ELISAs, and binding affinity was determined using surface plasmon resonance. Focal stroke was induced in C57Bl/6 mice by middle cerebral artery occlusion for 1 hour followed by reperfusion for 23 or 47 hours. Mice were treated intravenously with either bovine serum albumin (10 μg) or CBP (10 μg) at the commencement of reperfusion. At 24 or 48 hours, we assessed plasma levels of the chemokines CCL2/MCP-1 and CXCL2/MIP-2, as well as neurological deficit, brain leukocyte infiltration, and infarct volume.

Results—The CBP interacted with a broad spectrum of CC, CXC, and XC chemokines and bound CCL2/MCP-1 and CXCL2/MIP-2 with high affinity (pM range). Stroke markedly increased plasma levels of CCL2/MCP-1 and CXCL2/MIP-2, as well as numbers of microglia and infiltrating leukocytes in the brain. Increases in plasma chemokines were blocked in mice treated with CBP, in which there was reduced neurological deficit, fewer brain-infiltrating leukocytes, and ≈50% smaller infarcts at 24 hours compared with bovine serum albumin–treated mice. However, CBP treatment was no longer protective at 48 hours.

Conclusions—Post-stroke administration of CBP can reduce plasma chemokine levels in association with temporary attenuation of brain inflammation and infarct volume development. (Stroke. 2015;46:00-00. DOI: 10.1161/STROKEAHA.114.007298.)

Key Words: chemokines ■ chemokine binding protein ■ infarct ■ ischemia-reperfusion ■ leukocytes ■ middle cerebral artery occlusion

Stroke accounts for >10% of all deaths, as well as prolonged disability of one third of survivors. Approximately 80% of all adult strokes are ischemic in origin. After a disruption of blood supply to the brain, an infarct develops, comprising a central core of dead neurons surrounded by a penumbra of surviving but compromised tissue that is vulnerable to further inflammation-related injury or death caused by infiltrating immune cells.

Chemokines are a family of chemotactic cytokines that attract leukocytes toward a site of injury. Thus, together with their receptors expressed on leukocytes, chemokines play a crucial role in the extravasation and migration of leukocytes under inflammatory conditions. In the highly inflammatory setting of acute ischemic stroke, chemokines are generated by brain-resident microglial cells and infiltrating immune cells, resulting in further leukocyte attraction and activation.

Chemokines and their cognate receptors regulate both physiological and pathological processes in the central nervous system, and it is currently postulated that chemokines play a generally deleterious role by contributing to brain injury after cerebral ischemia–reperfusion.

We have shown that expression of numerous chemokine-related genes is upregulated in the mouse brain from 4 hours for ≥3 days after ischemia–reperfusion, raising the possibility that certain key chemokines/chemokine receptors could represent targets for acute stroke therapy. For example, we...
Neurological Assessment and Quantification of Infarct Volume

Neurological deficit was evaluated in all mice at 24 hours, and in some mice at 48 hours, in a blinded fashion using a 5-point scoring system.
Flow Cytometry
Quantitative analysis of immune cell subsets was conducted as previously described. In brief, 35 mice (12 sham-operated, 12 BSA-treated post-stroke; 11 CBP-treated post-stroke) were deeply anesthetized with inhalation of isoflurane, followed by decapitation. The brain was removed immediately and snap-frozen in liquid nitrogen. Coronal sections (30 μm thickness; separated by ≈420 μm) were obtained and stained with 0.1% thionin to delineate the infarct using ImageJ software (NIH, Bethesda, MD).

Chemokine ELISAs
The concentrations of CCL2/MCP-1 and CXCL2/MIP-2 in plasma from separate mice (not used for flow cytometric analyses) were assessed by ELISA using Q-Plex or DuoSet kits following the manufacturer’s instructions. Specifically, plates were coated with capture antibody, blocked, and then incubated with serial dilutions of plasma and chemokine standards for 1 hour at room temperature. The captured chemokine was then detected and quantified as described above.

Results
CBP Binds a Broad Spectrum of CC, CXC, and C Chemokines With High Affinity
Certain characteristics of the parapoxvirus CBPs have previously been described. The CBP from orf virus, the type species of the parapoxvirus genus, binds a range of CC, CXC, and C chemokines with high affinity and can neutralize the activity of CC chemokines in vitro and in vivo. Publication of the complete genome sequence of another parapoxvirus, BPSV strain AR-02 revealed an equivalent CBP ≈24 kb from the right terminus of the genome. We therefore sequenced the corresponding region in the BamHI A fragment of the genome from BPSV strain V660 and identified an equivalent CBP. The sequence of the BPSV V660 CBP has been deposited in GenBank under accession no. KM400588. The CBP from BPSV V660 is predicted to be 298 aa in length with a 19 aa signal peptide. The predicted proteins from the 2 BPSV strains share 95% identity, whereas both share only 42% identity with the orf virus CBP.

The CBP from BPSV V660 was expressed with a C-terminal FLAG octapeptide and then purified. Chemokine-binding activity of the purified protein was then assessed using an ELISA. The CBP was found to bind all CC and C chemokines tested, including CCL2/MCP-1, CCL3/MIP-1α, CCL5/RANTES, CCL19/MIP-3α, and XCL1/lymphotactin (Figure 1A and 1B). The CBP also interacted with CXCL2/MIP-2 and CXCL4/PF4 but did not bind CXCL8/IL-8, CXCL10/IP10, or CXCL12/SDF-1 (Figure 1C). To confirm its broad spectrum binding across different classes of chemokines, we investigated the binding affinity of the CBP for murine CCL2/MCP-1, XCL1/lymphotactin, and CXCL2/MIP-2 using surface plasmon resonance (Table II in the

Figure 1. Chemokine-binding activity measured by ELISA. CC chemokines (A), C chemokine (B), and CXC chemokines (C) were incubated with increasing amounts of the chemokine-binding protein (CBP). Unbound chemokine was then detected using a capture ELISA. Results are presented as a percentage of total chemokine detected in the absence of an inhibitor. A high percentage indicates no interference in the detection of the chemokine (no chemokine binding), whereas a low percentage indicates interference with detection (positive chemokine binding). Values are mean ± standard deviation (n=6).
online-only Data Supplement). The CBP showed highest affinity for CCL2/MCP-1 (KD value of 0.186 nmol/L), whereas it bound XCL1/lymphotactin and CXCL2/MIP-2 with slightly lower affinity (0.725 and 1.358 nmol/L, respectively). Each chemokine bound the CBP with fast association kinetics, but the rate of dissociation was much slower for CCL2/MCP-1.

Cerebral Blood Flow and Neurological Deficit
To test the effect of CBP on various outcome measures after stroke, mice were intravenously injected with 10 μg CBP or BSA (as a control protein) at the commencement of reperfusion after 1 hour MCA occlusion. Cerebral ischemia was confirmed in all animals by ~80% reduction in regional cerebral blood flow during 1 hour MCA occlusion (Figure 2A). Blood flow transiently returned to ~100% of the preischemic level after injection of BSA or CBP at the commencement of reperfusion, although mice treated with CBP tended to have a slightly higher mean level of flow for the remaining 20 minutes recording period (Figure 2A). At 24 hours, CBP-treated mice had a lower median neurological deficit score than those treated with BSA (Figure 2B). Moreover, 7 of 26 (27%) BSA-treated mice but only 1 of 19 (5%) CBP-treated mice received the most severe score (score of 4). Further, 2 of 26 (8%) BSA-treated mice compared with 7 of 19 (37%) CBP-treated mice received a score of 0, indicating no deficit. However, by 48 hours, median neurological deficit score had worsened in CBP-treated mice such that deficit was now equivalent to those that had been treated with BSA (Figure 2B).

Plasma Chemokines
Compared with sham-operated mice, plasma levels of both CCL2/MCP-1 and CXCL2/MIP-2 were increased by >25-fold at 24 hours in control mice subjected to cerebral ischemia-reperfusion (Figure 3A and 3B). Between 24 and 48 hours, plasma chemokine levels in control mice declined by ~50%, but nonetheless remained elevated compared with the sham control group (Figure 3). By contrast, in CBP-treated mice, plasma levels of both CCL2/MCP-1 and CXCL2/MIP-2 were similar to levels in sham-operated mice at both the 24 and 48 hours time points (Figure 3). In preliminary experiments, we also tested the effect of a 10-fold lower dose of CBP (1 μg, n=9) on plasma chemokine levels at 24 hours after stroke and found it to cause reductions of only ~20% versus BSA control treatment (CBP 1 μg versus BSA for CCL2/MCP-1: 950±278 pg/mL versus 1113±466 pg/mL; CXCL2/MIP-2: 921±332 pg/mL versus 1205±566 pg/mL), and so in subsequent experiments, only the 10 μg dose of CBP was studied.

Flow Cytometric Analysis of Leukocytes in Brain, Blood, and Spleen
There was a 3-fold increase in the total number of leukocytes present in the brains of control mice at 24 hours after cerebral ischemia compared with sham-operated mice (P<0.05, n=6–7; Figure 4A). However, in mice treated with CBP after stroke, leukocyte numbers in the brain at 24 hours were reduced almost to sham levels (Figure 4A). This profile of effect was also seen for individual cell types, including neutrophils, T cells, and monocytes, whereas the increased number of macrophages in the brain after stroke tended to be unaffected by CBP treatment (Figure 4B). Furthermore, in control mice, stroke increased the number of microglia in the brain by ~3-fold at 24 hours, but this effect was virtually abolished by CBP treatment (Figure 4C). From 24 to 48 hours after stroke in control mice, the numbers of infiltrating neutrophils, macrophages, and monocytes further increased by ~2-fold, whereas numbers of T cells and microglia declined (Figure 4B and 4C). Moreover, by 48 hours in CBP-treated
mice, the numbers of total leukocytes, neutrophils, macrophages, and monocytes all tended to be even higher than those measured in the brains of control mice, whereas numbers of T cells and microglia were no longer elevated above sham levels (Figure 4A–4C).

Cerebral ischemia–reperfusion resulted in 2- to 3-fold greater numbers of total leukocytes, neutrophils, T cells, and monocytes in blood at 24 hours (Figure 5A–5D), but no change in cell numbers in the spleen at 24 hours (Figure 1A–1F in the online-only Data Supplement). In contrast to its effects in the post-stroke brain, CBP had no effect on immune cell numbers in either the blood (Figure 5A–5D) or spleen (Figure 1A–1F in the online-only Data Supplement).

Infarct Analysis

Total and cortical infarct volumes and also edema volume were all smaller in CBP-treated versus control mice at 24 hours (Figure 6A–6C; Figure IIA and IIB in the online-only Data Supplement). Subcortical infarct volume also tended to be ≈40% smaller at 24 hours in mice treated with CBP compared with control mice (Figure 6D; Figure IIC in the online-only Data Supplement). Infarct and edema volumes were

![Figure 4](image4.png)

**Figure 4.** Flow cytometric quantification of leukocytes in the brain at 24 and 48 h after cerebral ischemia–reperfusion. A, Total CD45+ leukocytes; B, Ly6G+ neutrophils, CD3+ T cells, Ly6C+ monocytes, F4/80+ macrophages; and C, CD45+ intermediate/F4/80+ microglial cells (sham, n=6 at 24 h and n=6 at 48 h; control, n=7 at 24 h and n=5 at 48 h; chemokine-binding protein [CBP], n=5 at 24 h and n=6 at 48 h). Data are means±SEM cells per hemisphere (***P<0.001; **P<0.01; *P<0.05).

![Figure 5](image5.png)

**Figure 5.** Number of circulating leukocytes measured by flow cytometric analysis at 24 h after stroke. A, Total CD45+ leukocytes; B, Ly6G+ neutrophils; C, CD3+ T cells; D, Ly6C+ monocytes (sham, n=6; control, n=7; chemokine-binding protein [CBP], n=5). Data are presented as means±SEM cells per 5×10^5 cell events.
similar in control mice at 24 and 48 hours post-stroke; however, at 48 hours, the volume of infarcted tissue and swelling had increased in CBP-treated mice such that there was no longer any difference from control mice (Figure 6A–6D; Figure IID–IIF in the online-only Data Supplement).

Discussion

This is the first study to investigate the use of a broad spectrum viral CBP to assess the effects of chemokine-induced cell migration on stroke outcome in mice. After the identification and generation of a recombinant CBP from the parapoxvirus, BPSV, we confirmed its interaction with a broad spectrum of CC, C, and CXC chemokines and its ability to bind CCL2/MCP-1, XCL1/lymphotactin, and CXCL2/MIP-2 with high affinity. The chemokine-binding spectrum and affinities of the BPSV CBP were consistent with those reported for the CBP from its fellow parapoxvirus, orf virus. After establishing the ability of the CBP to inhibit a broad spectrum of chemokines, we investigated its efficacy in vivo. We found that intravenous administration of the CBP after transient cerebral ischemia largely prevented stroke-induced increases in circulating levels of key chemokines in association with milder neurological deficit at 24 hours. Flow cytometric analysis revealed that treatment with CBP also attenuated leukocyte infiltration in the brain after stroke. In addition, early development of brain infarct and swelling were markedly reduced in mice treated with CBP compared with control mice injected with BSA. Our data therefore support the concept that chemokines are key contributors to brain inflammation and injury in the initial stages after cerebral ischemia–reperfusion. Thus, post-stroke systemic administration of a therapy to broadly target and bind chemokines can provide temporary neuroprotection by delaying leukocyte infiltration into the injured brain.

We first examined the effect of post-stroke intravenous administration of CBP on the circulating levels of chemokines that are representative of CC and CXC families, namely CCL2/MCP-1 and CXCL2/MIP-2, respectively. These chemokines are produced by several cell types, including endothelial cells, monocytes, astrocytes, and microglia, and their expression is known to be markedly upregulated in the mouse model of transient cerebral ischemia used here. Our data confirm that plasma levels of CCL2/MCP-1 and CXCL2/MIP-2 remain increased by >25-fold at 24 hours and by >10-fold at 48 hours after cerebral ischemia–reperfusion in control mice and indicate that CBP treatment prevented these increases. These findings suggest that injection of this novel broad spectrum CBP after stroke can effectively target and remove multiple proinflammatory chemokines from the circulation.

We next examined the effect of CBP treatment on the numbers of circulating leukocytes and of those infiltrating the brain after stroke. We confirmed that stroke increases the number of leukocytes present in both the blood and ischemic brain hemisphere of control mice at 24 hours after cerebral ischemia. Despite having no effect on the number of leukocytes in the blood at this time, CBP treatment markedly reduced leukocyte numbers in the brain after stroke. This effect was due mainly to a reduction in infiltrating neutrophils, T cells, and monocytes. We also found that stroke increased the number of microglia in the brain by 3-fold at 24 hours and that CBP treatment prevented this increase over 48 hours. An important role of microglia in the ischemic brain is to phagocytose debris in damaged tissue, neutrophils, and apoptotic cells that have the potential to release damaging molecules. Indeed, CCL2/MCP-1 overexpression in the brain is reported to result in increased microglial activation, whereas CCL2/MCP-1-deficient mice exhibit impaired microglial accumulation and reduced leukocyte infiltration in numerous neuroinflammatory diseases.

In association with delayed leukocyte infiltration in the post-ischemic brain, we found that infarct development was retarded in CBP-treated mice. Such a profound effect from a single post-stroke administration of CBP is noteworthy and is conceptually consistent with data from mice with genetically modified levels of chemokine expression. For example, infarct volume is larger in CCL2/MCP-1-overexpressing mice, whereas global
CCL2/MCP-1 deficiency results in delayed infarct development associated with less severe blood–brain barrier disruption. With reference to this latter study, our data thus indicate that systemic administration of a CBP immediately after cerebral ischemia–reperfusion can achieve therapeutic neuroprotection that is comparable to that seen in animals that are globally deficient in chemokines. It is also interesting to note that CBP treatment effectively prevented T cell infiltration into the ischemic brain for 48 hours, during which time neurologic deficits and infarct volume developed to similar levels as in control mice. This observation would tend to argue against a major overall role of T cells in causing post-stroke brain injury, although it is plausible that the lack of T regulatory cells in the brain was detrimental. In addition to directly interacting with chemokines, CBP could decrease chemokine synthesis, but we think this to be unlikely. We have found that CBP administration has no immediate effects on inflammatory chemokine or cytokine expression in skin, but levels do eventually decrease because of the reduced influx of inflammatory cells expressing the same proteins. Moreover, we have observed no inhibition of chemokine expression by CBPs when administered to cultured monocytes (data not shown).

An emerging paradigm is that there are temporal changes in the hierarchy of chemotactic molecules in injured or infected tissue, such that end target chemotaxtrants (eg, complement component C5a or bacterial products) ultimately override the signals delivered by chemokines (ie, “intermediate” chemotaxtrants) released at intermediary sites, such as the endothelium. It is noteworthy that neutrophils—which preferentially respond to end target chemotaxtrants— comprise >50% of the leukocytes infiltrating the ischemic brain at 48 hours. We therefore predict that sustained protection from leukocyte-mediated brain injury after stroke will require effective targeting of chemokines together with other important chemotaxtrants. Indeed, delaying infarct development and neurological deficits by targeting early chemokine-dependent mechanisms of injury after stroke could be beneficial, perhaps by extending the window of opportunity for other treatments to be administered.

Sources of Funding

These studies were supported by a Project Grant from the National Health and Medical Research Council of Australia (NHMRC; ID 1010984) and a Programme Grant from the Health Research Council of New Zealand (10050). We also acknowledge support from NHMRC Senior Research Fellowships (GRD and CGS), Norhiro Ueda for his contribution to the sequencing and cloning of the bovine papular stomatitis virus chemokine binding protein, and Michael Corbett for his contribution to the development of the chemokine activity assay.

Disclosures

None.

References


Effect of a Broad-Specificity Chemokine-Binding Protein on Brain Leukocyte Infiltration and Infarct Development

Seyoung Lee, Hannah X. Chu, Hyun Ah Kim, Nicola C. Real, Saeed Sharif, Stephen B. Fleming, Andrew A. Mercer, Lyn M. Wise, Grant R. Drummond and Christopher G. Sobey

Stroke. published online December 23, 2014;

Stroke is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2014 American Heart Association, Inc. All rights reserved.
Print ISSN: 0039-2499. Online ISSN: 1524-4628

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://stroke.ahajournals.org/content/early/2014/12/23/STROKEAHA.114.007298

Data Supplement (unedited) at:
http://stroke.ahajournals.org/content/suppl/2015/01/30/STROKEAHA.114.007298.DC1

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Stroke can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Stroke is online at:
http://stroke.ahajournals.org//subscriptions/
Effect of A Broad Specificity Chemokine Binding Protein on Brain Leukocyte Infiltration and Infarct Development

Seyoung Lee BSc(Hons)\textsuperscript{1}, Hannah X Chu BSc(Hons)\textsuperscript{1}, Hyun Ah Kim PhD\textsuperscript{1}, Nicola C Real BSc(Hons)\textsuperscript{2}, Saeed Sharif MSc\textsuperscript{2}, Stephen B Fleming PhD\textsuperscript{2}, Andrew A Mercer PhD\textsuperscript{2}, Lyn M Wise PhD\textsuperscript{2}, Grant R Drummond PhD FAHA\textsuperscript{1,3} and Christopher G Sobey PhD FAHA\textsuperscript{1,3}

1. Department of Pharmacology, Monash University, Clayton, Victoria 3800, Australia.
2. Department of Microbiology and Immunology, University of Otago, PO Box 56, Dunedin, New Zealand.
3. Department of Surgery, Southern Clinical School, Monash University, Clayton, Victoria, Australia.

Author for Correspondence:
A/Prof Christopher G. Sobey
Vascular Biology and Immunopharmacology Group
Department of Pharmacology
Monash University
Clayton
Victoria 3800
Australia
Telephone: +61 3 9905 4189
Fax: +61 3 9902 9500
E-mail: chris.sobey@monash.edu
### Supplementary Table I: Antibody used for flow cytometry.

<table>
<thead>
<tr>
<th>Antigen</th>
<th>Host/Isotype</th>
<th>Clone</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>B220</td>
<td>Rat IgG2a</td>
<td>RA3-6B2</td>
<td>Invitrogen</td>
</tr>
<tr>
<td>CD11b</td>
<td>Rat IgG2b, kappa</td>
<td>M1/70</td>
<td>eBioscience</td>
</tr>
<tr>
<td>CD3</td>
<td>Syrian Hamster IgG2, kappa</td>
<td>500A2</td>
<td>BD Biosciences</td>
</tr>
<tr>
<td>CD45</td>
<td>Rat IgG2b, kappa</td>
<td>30-F11</td>
<td>BioLegend</td>
</tr>
<tr>
<td>CD49b</td>
<td>ArHam IgG</td>
<td>HMa2</td>
<td>BioLegend</td>
</tr>
<tr>
<td>CD90.2</td>
<td>Rat IgG2b, kappa</td>
<td>30-H12</td>
<td>BioLegend</td>
</tr>
<tr>
<td>F4/80</td>
<td>Rat IgG2a, kappa</td>
<td>BM8</td>
<td>eBioscience</td>
</tr>
<tr>
<td>Ly6C</td>
<td>Rat IgG2c, kappa</td>
<td>HK1.4</td>
<td>BioLegend</td>
</tr>
<tr>
<td>Ly6G</td>
<td>Rat IgG2a, kappa</td>
<td>1A8</td>
<td>BioLegend</td>
</tr>
<tr>
<td>NK1.1</td>
<td>Mouse IgG2a, kappa</td>
<td>PK136</td>
<td>BioLegend</td>
</tr>
<tr>
<td>7-Amino-actinomycin D (7AAD)</td>
<td>-</td>
<td>-</td>
<td>Invitrogen</td>
</tr>
</tbody>
</table>

### Supplementary Table II: Binding affinity of BPSV CBP to murine chemokines.

<table>
<thead>
<tr>
<th>Chemokines</th>
<th>$k_a$ (x10^6) M^{-1}s^{-1}</th>
<th>$k_d$ (x10^{-3}) s^{-1}</th>
<th>$k_D$ (nM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCL2/MCP-1</td>
<td>1.18 ± 0.004</td>
<td>0.220 ± 0.005</td>
<td>0.186</td>
</tr>
<tr>
<td>XCL1/lymphotactin</td>
<td>0.99 ± 0.02</td>
<td>1.35 ± 0.01</td>
<td>1.358</td>
</tr>
<tr>
<td>CXCL2/MIP-2</td>
<td>0.77 ± 0.004</td>
<td>0.56 ± 0.003</td>
<td>0.725</td>
</tr>
</tbody>
</table>
Supplementary Figure I

Populations of leukocytes in the spleen measured by flow cytometric analysis. (A) Total CD45+ leukocytes, (B) Ly6G+ neutrophils, (C) CD49b+ CD90+, NK1.1+, B220+ lymphoid cells, (D) CD3+ T cells, (E) F4/80+ macrophages, (F) Ly6C+ monocytes (Sham, n=6; Control, n=7; CBP, n=5). Data are mean ± SEM cells per 2x10^5 cell events.

Spleen Leukocytes: 24 h
Supplementary Figure II

Total (A, D), cortical (B, E), and subcortical (C, F) brain infarct distribution in Control and CBP-treated mice at 24 h (Control, n=11; CBP, n=6) or 48 h (Control, n=9; CBP, n=5).