

Proximal Cerebral Arteries Develop Myogenic Responsiveness in Heart Failure via Tumor Necrosis Factor- α -Dependent Activation of Sphingosine-1-Phosphate Signaling

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Background—Heart failure is associated with neurological deficits, including cognitive dysfunction. However, the molecular mechanisms underlying reduced cerebral blood flow in the early stages of heart failure, particularly when blood pressure is minimally affected, are not known.

Methods and Results—Using a myocardial infarction model in mice, we demonstrate a tumor necrosis factor- α (TNF α)-dependent enhancement of posterior cerebral artery tone that reduces cerebral blood flow before any overt changes in brain structure and function. TNF α expression is increased in mouse posterior cerebral artery smooth muscle cells at 6 weeks after myocardial infarction. Coordinately, isolated posterior cerebral arteries display augmented myogenic tone, which can be fully reversed in vitro by the competitive TNF α antagonist etanercept. TNF α mediates its effect via a sphingosine-1-phosphate (S1P)-dependent mechanism, requiring sphingosine kinase 1 and the S1P₂ receptor. In vivo, sphingosine kinase 1 deletion prevents and etanercept (2-week treatment initiated 6 weeks after myocardial infarction) reverses the reduction of cerebral blood flow, without improving cardiac function.

Conclusions—Cerebral artery vasoconstriction and decreased cerebral blood flow occur early in an animal model of heart failure; these perturbations are reversed by interrupting TNF α /S1P signaling. This signaling pathway may represent a potential therapeutic target to improve cognitive function in heart failure. (*Circulation*. 2012;126:196-206.)

Key Words: cerebrovascular circulation ■ myocardial infarction ■ signal transduction ■ sphingosine kinase ■ vasomotor system

This investigation sought to define the molecular mechanisms underlying reduced cerebral blood flow (CBF) in the early stages of heart failure (HF), when blood pressure remains minimally affected. Previous investigations have attempted to correlate reduced CBF in HF with deteriorating cardiac output (CO).¹⁻⁴ However, the correlation between CO and CBF is complex and depends on how cerebrovascular autoregulation adapts in HF. Under physiological conditions, autoregulation ensures that patients with adequate cerebro-

vascular reactivity can compensate for reduced CO by lowering cerebrovascular resistance (via dilation of brain arterioles).⁵ However, clinical data suggest that under conditions of HF, cerebrovascular resistance actually increases,^{3,4} although vasodilation should prevail. Enhanced vasoconstriction in HF may seriously compromise CBF autoregulation, creating the scenario in which further drops in CO may not be tolerated and the risk of developing structural and functional brain deficits may be increased.

Received October 7, 2010; accepted May 18, 2012.

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The online-only Data Supplement is available with this article at <http://circ.ahajournals.org/lookup/suppl/doi:10.1161/CIRCULATIONAHA.111.039644/-/DC1>.

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Circulation is available at <http://circ.ahajournals.org>

DOI: 10.1161/CIRCULATIONAHA.111.039644

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Blood flow autoregulation relies on the property of cerebral arteries to adjust their flow resistance, via changes in vessel diameter, to the prevalent transmural pressure (ie, the myogenic response or Bayliss effect^{6,7}) and to maintain constant CBF over a wide range of systemic pressures (60- to 150-mm Hg mean arterial pressure).⁸ To ensure that CBF regulation has fine spatial resolution (ie, the ability to precisely and selectively increase flow to active brain volumes), different branch generations of the cerebrovascular tree are structurally and functionally specialized. The distal resistance arteries, which are located just before the capillary beds, exhibit the largest degree of myogenic activity and integrate modulatory influences of tissue-derived signaling molecules.⁹ Proximal cerebral arteries minimally restrict blood flow (ie, maintain a low-resistance profile) and ultimately display a functional pattern very similar to that of conduit arteries in the systemic circulation (ie, minimal myogenic activity). Therefore, high levels of myogenic tone in proximal cerebral arteries may result in widespread reductions in CBF.

With regard to the molecular basis for the myogenic response, sphingosine-1-phosphate (S1P) signaling has emerged as a central pathway in several vascular beds, including cerebral arteries.^{10–12} The procontractile effects of S1P are mediated primarily via the S1P₂ receptor,^{11–13} which activates RhoA/Rho kinase and ultimately inhibits myosin light-chain phosphatase.¹⁴ The central element of this pressure-sensitive signaling pathway in smooth muscle cells is sphingosine kinase 1 (Sphk1), which generates S1P. Thus, factors known to modulate Sphk1 activity are candidates for altering myogenic responsiveness.

The inflammatory cytokine tumor necrosis factor- α (TNF α) is a well-characterized activator of Sphk1^{15–17} and a hallmark of several cardiovascular^{18,19} and cerebrovascular^{20–22} diseases. Indeed, recent *in vitro* measurements using the spiral modiolar artery (a cochlear artery) indicate that TNF α activates smooth muscle cell Sphk1 to induce a procontractile state throughout the cochlear microcirculation.²³ In addition, TNF α has been shown to elicit vasoconstriction in both human mammary arteries²⁴ and mouse cerebral arteries.²⁵ However, the ability of TNF α to link a systemic disease like HF to altered control of CBF had not been explored.

Here, we show that proximal cerebral arteries, which normally possess minimal myogenic activity, are recruited to become myogenically active in HF and that TNF α is the primary factor driving this recruitment through activation of S1P signaling. Our results provide a microvascular concept that explains the association between HF and the decrease in CBF.

Methods

Mouse Nomenclature

All wild-type mice used in this investigation were commercially available C57BL/6N mice. Mice lacking Sphk1 (*Sphk1*^{-/-}), sphingosine kinase 2 (*Sphk2*^{-/-}), the S1P₂ receptor subtype (*S1P₂R*^{-/-}), and a double mutant with complete deletion of Sphk1 and heterozygosity for Sphk2 (*Sphk1*^{-/-}/*Sphk2*[±]) were kindly provided by Dr Richard L. Proia (Bethesda, MD). Unless otherwise designated,

arteries were isolated from naïve mice; all mice operated on to induce HF or to create a sham controls were designated as such.

Myocardial Infarction

HF in mice was induced by experimental myocardial infarction produced by permanent surgical ligation of the left anterior descending coronary artery (LAD), as previously described.¹² In sham-operated controls, the thorax and pericardium were opened, but the LAD was not ligated. After either procedure, the chest was closed and the mice were extubated on spontaneous respiration. Cerebral arteries were isolated 4 to 6 weeks after myocardial infarction. As described, HF (infarct size approximating 25% of the left ventricular wall) mice develop enlarged hearts, congested lungs, reduced CO and blood pressure, and elevated peripheral resistance.¹² All of these parameters remain normal in sham-operated controls.

Isolation and Functional Assessment of Cerebral Arteries

To demonstrate the longitudinal gradient of myogenic activity, posterior cerebral artery (PCA) segments from healthy gerbils were used; distal segments of gerbil PCAs were more reliable for experimentation, because of less frequent branching. All other experiments used proximal PCA segments from the mouse. After anesthesia, the animal was decapitated, and the brain was rapidly removed from the cranium and immersed in ice-cold sterile 3-(*n*-morpholino)propanesulfonic acid (MOPS) buffer. PCA segments (0.8–1.0 mm in length) were carefully dissected from the surrounding connective tissue. Only first-order vessels were isolated from mice (160–220 μ m), whereas first- and third- or fourth-order vessels were harvested from gerbils (160–220 and 90–150 μ m in diameter, respectively). The isolated vessel segments were cannulated on glass micropipettes, stretched to their *in vivo* lengths, and pressurized to 45 mm Hg, as previously described.²⁶ All functional experiments were conducted in MOPS-buffered saline at 37°C with no perfusion.

To measure myogenic responses, vessels were subjected to stepwise increases in transmural pressure (20-mm Hg increments) from 20 to 100 mm Hg. At each pressure step, vessel diameter (dia_{active}) was measured once a steady state was reached (3–5 minutes). Myogenic tone was calculated as the percent constriction in relation to the maximal diameter at each respective transmural pressure: tone (percent of dia_{max}) = $[(dia_{max} - dia_{active}) / dia_{max}] \times 100$, where dia_{active} is the vessel diameter in MOPS containing Ca²⁺ and dia_{max} is the diameter in Ca²⁺-free MOPS. Vasomotor responses (eg, phenylephrine, acetylcholine, Ca²⁺ sensitivity) used the same calculation, only in these cases, dia_{active} represents the vessel diameter at steady state after application of the given agent and dia_{max} represents the maximal diameter (measured under Ca²⁺-free conditions) at 45 mm Hg. Further details are provided in the online-only Data Supplement, and representative tracings are shown in Figure I in the online-only Data Supplement.

Immunohistochemistry and Reverse Transcriptase–Polymerase Chain Reaction

Standard immunohistochemical and biochemical procedures were used. Detailed methods are provided in the online-only Data Supplement.

Cerebral Blood Flow

A noninvasive magnetic resonance imaging–based method known as the flow-sensitive alternating inversion recovery technique was used to evaluate brain perfusion.²⁷ This technique is described in detail in the online-only Data Supplement. Briefly, the approach isolates perfusion as an accelerated T1 signal relaxation. Magnetic resonance imaging signals were acquired from vertical sections of the forebrain, midbrain, and hindbrain, which correspond to the anterior, mixed, and posterior circulations. Flow-sensitive alternating inversion recovery images were evaluated for designated regions of interest by the use of standardized algorithms and image processing

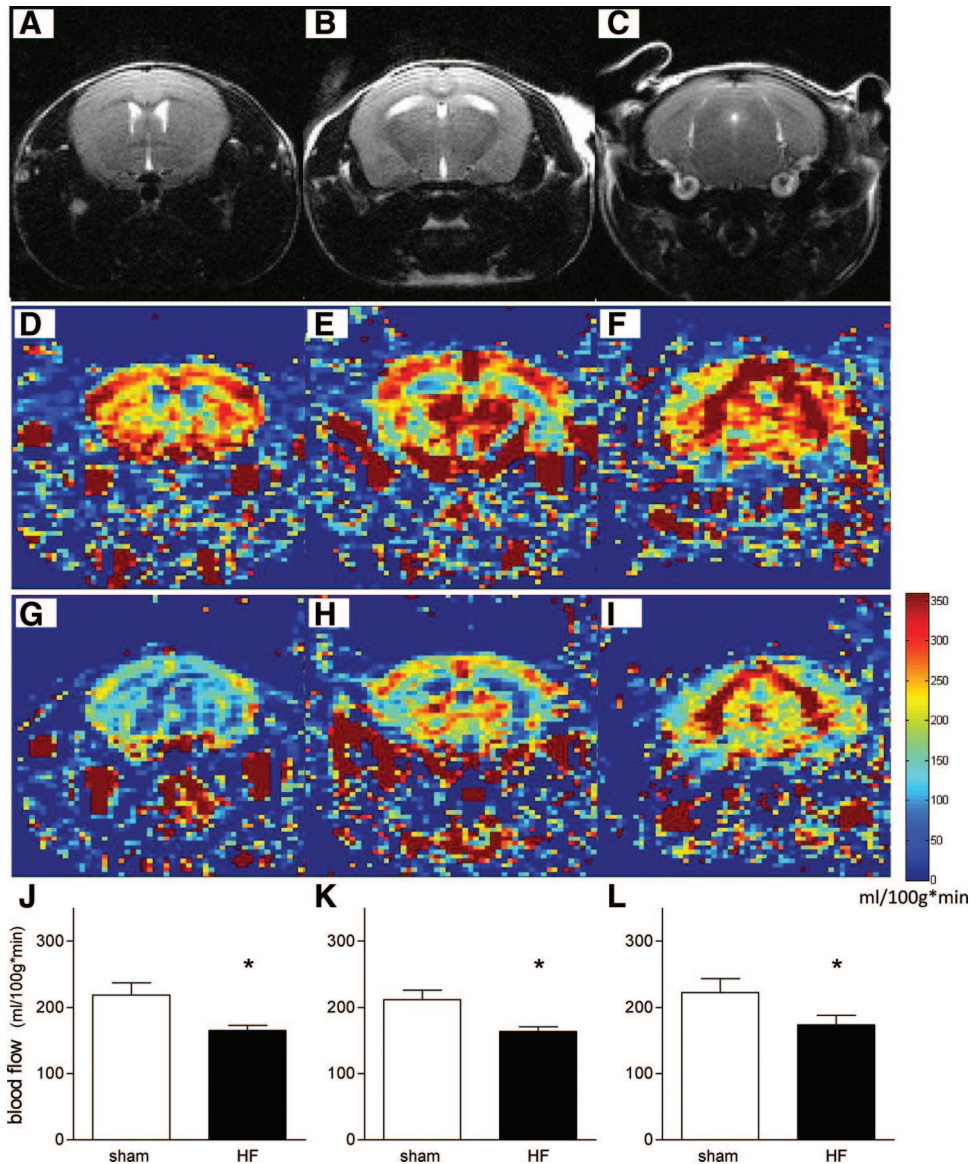


Figure 1. Heart failure (HF) reduces cerebral blood flow. Flow-sensitive alternating inversion recovery–magnetic resonance imaging of the forebrain (A), midbrain (B), and hindbrain (C) was used to assess blood flow in predefined cortical and subcortical brain regions of interest in sham (D–F) and HF (G–I) mice. HF significantly reduced global (J), cortical (K), and subcortical (L) blood flow compared with sham-treated mice (sham, $n=14$; HF, $n=16$). * $P<0.05$.

procedures (MIPAV; National Institutes of Health, Bethesda, MD; <http://www.mipav.cit.nih.gov/>).

Etanercept Treatment In Vivo

Six weeks after myocardial infarction, cohorts of HF mice were treated with either etanercept (1 mg/mL sc) or saline twice weekly for 2 weeks. Sham-operated mice served as controls. CBF²⁷ and hemodynamic parameters¹² were assessed as previously described.

Statistical Analysis

All data (including figures) are expressed as mean \pm SEM, where n is the number of vessels studied. An unpaired Student t test was used to compare 2 separate groups (eg, sham and HF). When appropriate (eg, before and after inhibitor), a paired Student t test was used. For comparison of multiple groups, an ANOVA followed by t tests with Bonferroni correction was used. Differences were considered significant at $P<0.05$.

Results

Magnetic Resonance Imaging–Demonstrable Reductions in CBF Occur Early in HF

CBF was measured in predefined cortical and subcortical regions of interest, and pooling of data from all regions of interest was used to assess global CBF in sham ($n=14$) versus HF (4–6 weeks after myocardial infarction; $n=16$) mice. Global (227 ± 10 versus 165 ± 8 mL \cdot 100 g⁻¹ \cdot min⁻¹; $P<0.05$), cortical (213 ± 11 versus 163 ± 7 mL \cdot 100 g⁻¹ \cdot min⁻¹; $P<0.05$), and subcortical (226 ± 14 versus 185 ± 17 mL \cdot 100 g⁻¹ \cdot min⁻¹; $P<0.05$) CBF was reduced in HF mice (Figure 1). Importantly, these reductions in CBF were not attributable to any changes in brain structure, as measured by high-resolution magnetic resonance imaging (Figure II in the online-only Data Supplement). Moreover, at this early stage of HF, mice did not manifest

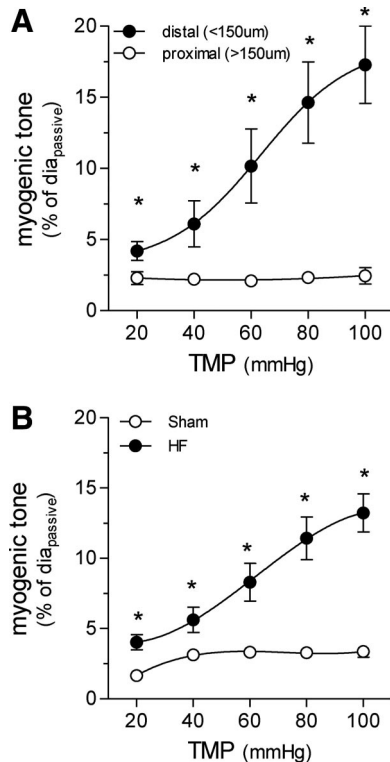


Figure 2. Heart failure (HF) enhances posterior cerebral artery (PCA) tone. **A**, Proximal (first order; passive external diameter at 45 mm Hg: $196 \pm 12 \mu\text{m}$) and distal (third or fourth order; passive external diameter at 45 mm Hg: $137 \pm 4 \mu\text{m}$) gerbil PCAs were subjected to stepwise increases in transmural pressure (TMP; 20–100 mm Hg). At each pressure step, myogenic tone was significantly larger in distal PCAs compared with proximal PCAs ($n=6$ for each group). **B**, Myogenic tone at every applied transmural pressure (20–100 mm Hg) was significantly enhanced in proximal PCAs isolated from mice with HF compared with sham-operated controls (sham, $n=6$; HF, $n=14$). * $P<0.05$.

cognitive abnormalities, as determined by the Morris water maze test (Figure III in the online-only Data Supplement).

HF Is Associated With Increased Myogenic Tone in Proximal Cerebral Arteries

In the gerbil, a larger animal enabling comparisons between proximal and distal cerebral vessels, we found that distal (third- or fourth-order) segments of the PCA normally exhibit greater resting tone (defined as tone at 45 mm Hg; distal, $7.1 \pm 2.7\%$; proximal, $1.9 \pm 0.2\%$; $n=6$; $P<0.05$) and significantly stronger myogenic tone at each applied pressure step (defined as tone over a range of 20–100 mm Hg in 20-mm Hg increments) compared with proximal (first-order) segments (Figure 2A).

In contrast, in mice with HF, both resting tone (sham, $3.0 \pm 0.3\%$, $n=6$; HF, $5.7 \pm 0.9\%$, $n=12$; $P<0.05$) and myogenic tone (Figure 2B) were significantly increased in proximal PCAs compared with sham-operated controls; passive external diameters did not differ (dia_{max} : sham, $197 \pm 2 \mu\text{m}$, $n=6$; HF, $195 \pm 3 \mu\text{m}$, $n=14$; $P=\text{NS}$).

Increased PCA Expression of TNF α Accounts for Enhanced Myogenic Tone in HF

Costaining of brain slices revealed increased TNF α expression in PCAs from mice with HF compared with sham

controls (Figure 3A). This increased TNF α expression appeared to be localized primarily to the smooth muscle compartment within the microvascular wall (virtually complete overlap of TNF α with smooth muscle α -actin staining; Figure 3B). Reverse transcriptase–polymerase chain reaction experiments using isolated PCAs confirmed a 2.5-fold increase in TNF α mRNA in HF versus sham (Figure 3C).

In PCAs isolated from wild-type mice with HF, etanercept (a competitive TNF α antagonist) fully normalized HF-stimulated enhancement of myogenic tone ($n=6$; Figure 3D). Consistent with this observation, treatment of PCAs isolated from naïve wild-type mice with TNF α (50 $\mu\text{g}/\text{mL}$ for 30 minutes) stimulated a significant increase in both resting tone ($2.4 \pm 0.1\%$ versus $4.5 \pm 0.5\%$; $n=5$; $P<0.05$, paired comparison) and myogenic tone (Figure 3E). Subsequent cotreatment with the putative S1P₂R antagonist JTE013 (1 $\mu\text{mol}/\text{L}$ for 30 minutes) abolished the TNF α -mediated increase in resting tone ($2.7 \pm 0.4\%$; $P=\text{NS}$, paired comparison with control) and myogenic tone (Figure 3E).

TNF α Increases Myogenic Tone in Mouse PCA via Sphk1 and S1P₂R

On the basis of our observation that an S1P₂R antagonist abolished TNF α -enhanced tone in PCAs from wild-type animals without HF, we hypothesized that the increased myogenic tone of PCAs from mice with HF might also be mediated by enhanced S1P/S1P₂R signaling via the known TNF α -dependent activation of the enzyme sphingosine kinase (*Sphk*).^{15–17,23} First, we confirmed that a low concentration of S1P (10 nmol/L, which does not stimulate vasoconstriction) has the ability to enhance resting and myogenic tone in wild-type mouse and gerbil PCAs (Table I in the online-only Data Supplement). Next, using loss-of-function mice (please note that the *Sphk1*^{-/-}/*Sphk2*^{-/-} double knockout is embryonically lethal), we observed that TNF α had no effect on PCAs from *Sphk1*^{-/-}, *Sphk1*^{-/-}/*Sphk2*^{+/-}, or *S1P₂R*^{-/-} mice (Figure 4). In contrast, TNF α stimulated a 2- to 3-fold increase in myogenic tone in mice lacking *Sphk2* (Figure 4A).

Enhanced Myogenic Tone in the PCA in HF Is Mediated by Activation of S1P Signaling

Unlike wild-type mice (Figure 2B), HF failed to augment myogenic tone in mice lacking *Sphk1* (Figure 5A). Importantly, the application of exogenous S1P (3 $\mu\text{mol}/\text{L}$) restored the HF phenotype and enhanced myogenic tone in PCAs isolated from both HF and sham *Sphk1*^{-/-} mice to similar extents (Figure 5A). Passive external diameters were not different (dia_{max} : *Sphk1*^{-/-} sham, $174 \pm 7 \mu\text{m}$, $n=6$; *Sphk1*^{-/-} HF, $173 \pm 8 \mu\text{m}$, $n=5$; $P=\text{NS}$; Figure 5A). Our model of HF also failed to increase myogenic tone in mice lacking the S1P₂ receptor (*S1P₂R*^{-/-}; Figure 5B). Again, passive diameters did not differ (dia_{max} : *S1P₂R*^{-/-} sham, $186 \pm 13 \mu\text{m}$, $n=5$; *S1P₂R*^{-/-} HF, $191 \pm 4 \mu\text{m}$, $n=6$; $P=\text{NS}$; Figure 5B). As with the TNF α -mediated enhancement of myogenic tone (Figure 3E), JTE013 reversed the HF-stimulated enhancement of myogenic tone observed in PCAs from wild-type mice (Figure 5C).

Taken together, these data demonstrate that the enhanced myogenic tone of PCAs that occurs in HF requires an intact S1P signaling system. To further establish the specificity of

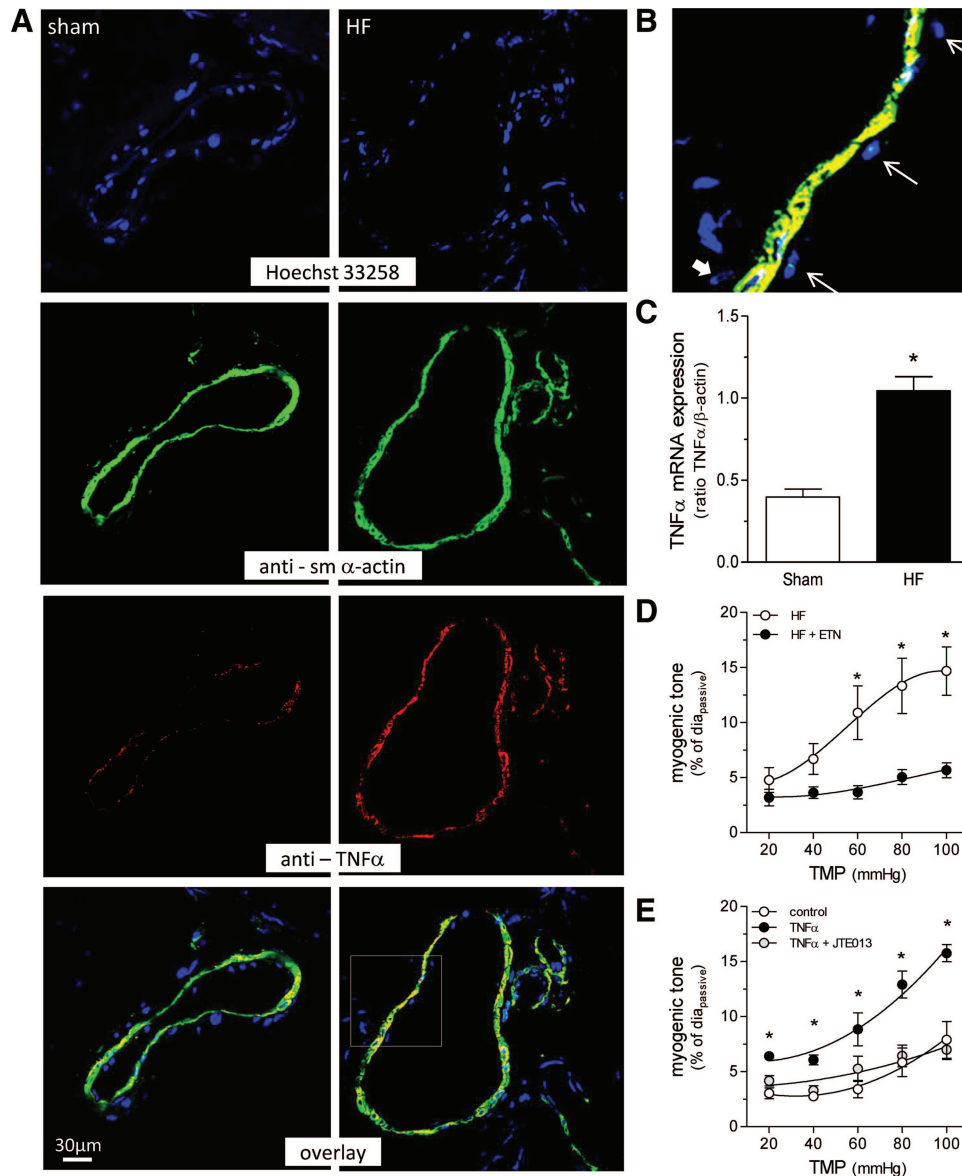


Figure 3. Tumor necrosis factor- α (TNF α) mediates the heart failure (HF)-induced increase in posterior cerebral artery (PCA) myogenic tone. **A**, Brain slices from HF and sham-operated animals containing a cross section of the PCA were costained with Hoechst 33258 (to identify cell nuclei) and antibodies against smooth muscle α -actin (sm α -actin) and TNF α . TNF α expression was increased homogeneously throughout the PCA vessel wall in HF mice (overlay). **B**, High-magnification confocal images demonstrate that the vast majority of TNF α expression was localized to the smooth muscle layer (colocalization of sm α -actin and TNF α generates yellow); TNF α expression was not observed in the endothelial (thin arrows identify endothelial nuclei) or adventitial (thick arrow identifies adventitial nuclei) layers. **C**, TNF α mRNA expression was higher in isolated PCAs from HF mice compared with sham-operated animals ($n=4$, each). **D**, The TNF α antagonist etanercept (ETN; 10 μ g/mL for 30 minutes; $dia_{max}=194\pm 3$ μ m; $n=6$) normalized the HF-mediated increase in myogenic tone. **E**, TNF α (50 pg/mL for 30 minutes) stimulated a significant enhancement of myogenic tone in wild-type PCAs that was reversed by subsequent treatment with JTE013 (1 μ mol/L for 30 minutes; $n=5$). TMP indicates transmural pressure.

our earlier observations with the TNF α antagonist etanercept (Figure 3D), we tested the effects of this agent in mice lacking components of S1P signaling. Etanercept had no effect on PCAs isolated from *Sphk1*^{-/-} or *Sphk1*^{-/-}/*Sphk2*^{+/-} mice with HF (Figure IV in the online-only Data Supplement). Although a small effect of etanercept was observed in PCAs from *SIP₂R*^{-/-} mice with HF (Figure V in the online-only Data Supplement), it was not enough to account for the complete normalization of myogenic tone observed in PCAs from wild-type mice with HF (Figure 3D).

HF Specifically Enhances S1P-Stimulated PCA Vasoconstriction

We next examined whether HF was associated with indiscriminate (ie, systematic) increases in PCA responsiveness or a more exclusive sensitivity to S1P. PCAs from sham mice displayed minimal vasoconstriction in response to exogenously applied S1P (30 nmol/L to 3 μ mol/L; Figure 6A), whereas PCAs from HF mice displayed robust dose-dependent vasoconstrictor responses to S1P (Figure 6A). In contrast, dose-response relationships for phenylephrine (\log_{EC50} : HF, -5.33 ± 0.34 ; sham,

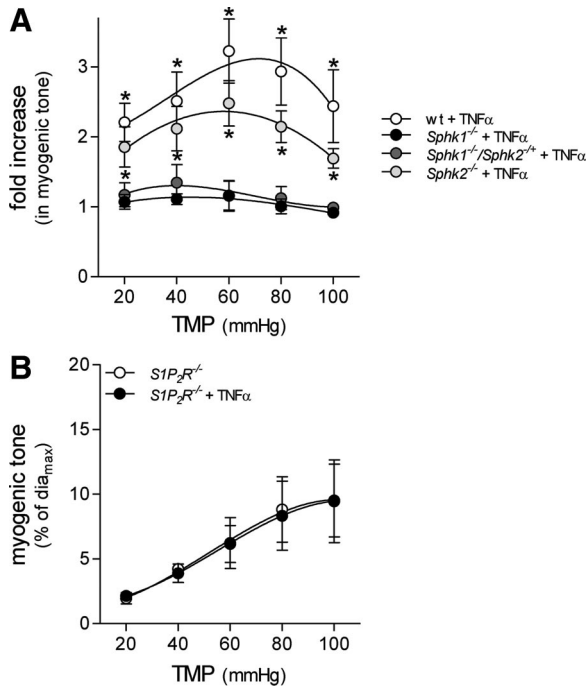


Figure 4. Tumor necrosis factor- α (TNF α) requires sphingosine kinase 1 (Sphk1) to increase myogenic tone in posterior cerebral arteries (PCAs). **A**, TNF α failed to enhance myogenic tone in PCAs isolated from *Sphk1*^{-/-} (dia_{max}=167 \pm 4 μ m; n=11) or *Sphk1*^{-/-}/*Sphk2*^{+/-} mice (dia_{max}=181 \pm 4 μ m; n=6). Mice lacking Sphk2 (*Sphk2*^{-/-}, n=5) showed TNF α -induced increases in myogenic tone that were not different from those observed in wild-type (wt) mice (n=8). Data are normalized to the untreated control level of myogenic tone. **B**, PCAs isolated from *S1P₂R*^{-/-} mice showed no increase in myogenic tone after TNF α treatment (50 pg/mL for 30 minutes; dia_{max}=188 \pm 12 μ m; n=4). **P*<0.05 for unpaired (**A**) and paired (**B**) comparisons. TMP indicates transmural pressure.

-5.33 \pm 0.27; *P*=NS; n=4 each; Figure 6B) and Ca²⁺ under depolarizing (120 mmol/L K⁺) conditions (log_{EC50}: HF, -3.28 \pm 0.05; sham, -3.31 \pm 0.05; *P*=NS; n=4 each; Figure 6C) were not affected by HF.

Lack of *Sphk1*^{-/-} Protects Against the HF-Induced Reduction in CBF

Our in vitro data predict that disrupting S1P signaling will ameliorate the HF-induced reduction in CBF. LAD ligation profoundly compromised cardiac performance in *Sphk1*^{-/-} mice, as evidenced by substantial reductions in stroke volume and CO (Table II in the online-only Data Supplement). A compensatory increase in total peripheral resistance maintained mean arterial pressure (MAP) in *Sphk1*^{-/-} mice, with HF at levels comparable to those in sham-operated mice (Table II in the online-only Data Supplement). Although MAP levels appeared to be lower than in the other tested cohorts, these observations are unlikely to be attributable to the *Sphk1*^{-/-} genotype.²⁸

Because autoregulation serves to maintain organ blood flow during fluctuations in perfusion pressure, the observed lack of correlation between CBF and MAP in *Sphk1*^{-/-} sham and HF mice indicates that autoregulatory mechanisms were functioning under both conditions (Figure 7). Despite intact autoregulation, CBF measures were qualitatively lower than

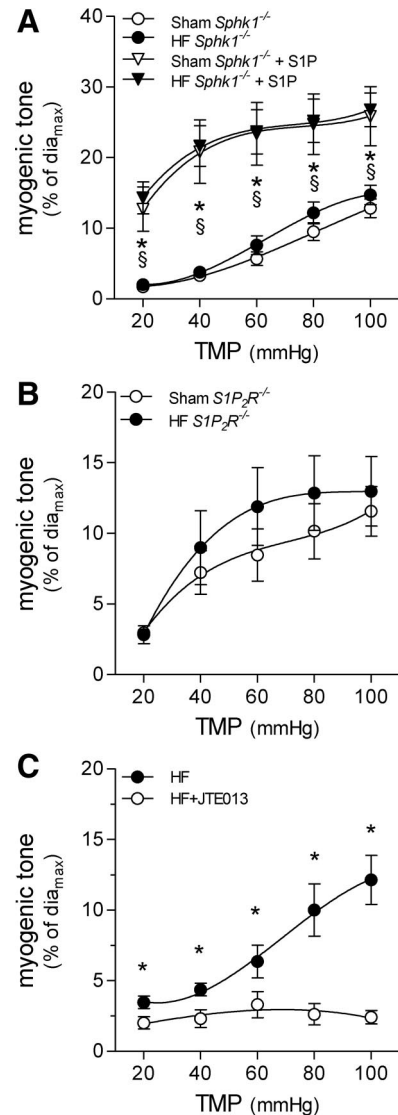


Figure 5. Increases in myogenic tone in heart failure (HF) require Sphk1 and the sphingosine-1-phosphate-2 receptor (S1P₂R). **A**, Myogenic tone in posterior cerebral arteries (PCAs) isolated from Sphk1 knockout mice with HF (*Sphk1*^{-/-} HF; n=5) did not differ from corresponding sham control (*Sphk1*^{-/-} sham; n=6; *P*=NS, unpaired comparison). Exogenous S1P (3 μ mol/L) enhanced myogenic tone in both groups to a similar extent (*P*=NS, unpaired comparison). **P*<0.05 for paired comparisons of *Sphk1*^{-/-} sham vs *Sphk1*^{-/-} sham+S1P; §*P*<0.05 for paired comparisons of *Sphk1*^{-/-} HF vs *Sphk1*^{-/-} HF+S1P. **B**, Myogenic tone in PCAs isolated from *S1P₂R* knockout mice with HF (*S1P₂R*^{-/-} HF; n=6) also did not differ (*P*=NS, unpaired comparison) from corresponding sham control (*S1P₂R*^{-/-} sham; n=5). **C**, JTE013 (1 μ mol/L for 30 minutes) reversed the enhancement of myogenic tone observed in PCAs isolated from wild-type mice with HF (n=8). **P*<0.05 for paired comparisons. TMP indicates transmural pressure.

in the other cohorts, suggesting the presence of a specific *Sphk1*^{-/-} phenotype. Our experimental design, however, did not include wild-type littermate controls; thus, we limit our analyses strictly to the sham and HF groups within the *Sphk1*^{-/-} cohort. In this specific context, HF did not alter CBF in *Sphk1*^{-/-} mice (Figure 7C), so we conclude that *Sphk1* is an integral component of the signaling pathway that reduces CBF in HF.

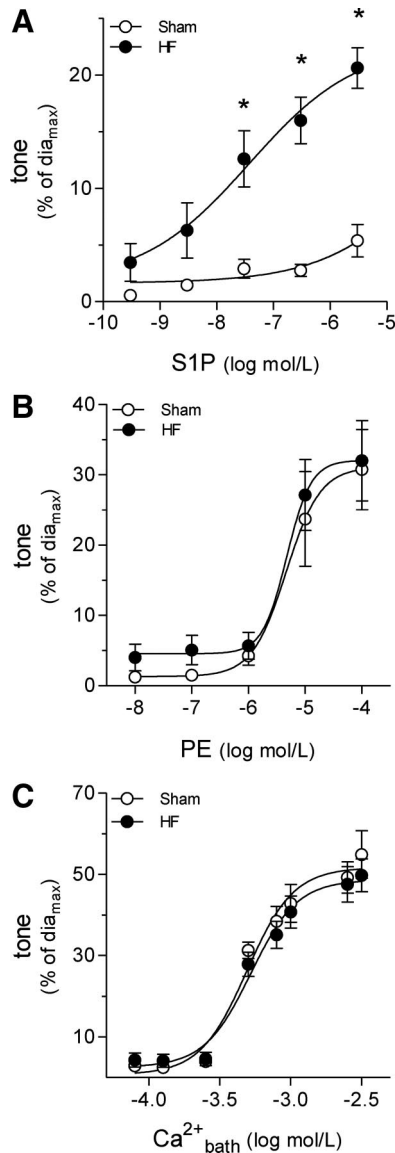


Figure 6. Heart failure (HF) selectively enhances sphingosine-1-phosphate (S1P)-induced constriction of posterior cerebral arteries (PCAs). **A**, S1P-stimulated vasoconstriction was significantly enhanced in PCAs isolated from mice with HF compared with sham controls (sham, $n=4$; HF, $n=9$). In contrast, dose-response relationships for **(B)** phenylephrine (PE; both groups, $n=4$) and **(C)** Ca^{2+} under depolarizing conditions (both groups, $n=4$) were unaffected by HF. All vasomotor response data were obtained at a transmural pressure of 45 mm Hg. * $P<0.05$ for unpaired comparisons; § $P<0.05$ for paired comparisons of HF vs HF+JTE013.

Systemic Etanercept Treatment of Mice in HF Improves Global CBF

We next attempted to therapeutically target the identified molecular pathway driving reduced CBF. In the absence of a clinically available S1P signaling antagonist, we used etanercept, a clinically available TNF α antagonist.

In initial experiments, the etanercept treatment was started 2 weeks after LAD ligation (1 mg/mL sc twice per week for 6 weeks). Etanercept treatment fully reversed the reduction in global CBF observed in HF (sham saline, $220\pm 8 \text{ mL} \cdot 100 \text{ g}^{-1} \cdot \text{min}^{-1}$, $n=8$; HF saline: $189\pm 7 \text{ mL}/100 \text{ g} \cdot \text{min}$, $n=8$;

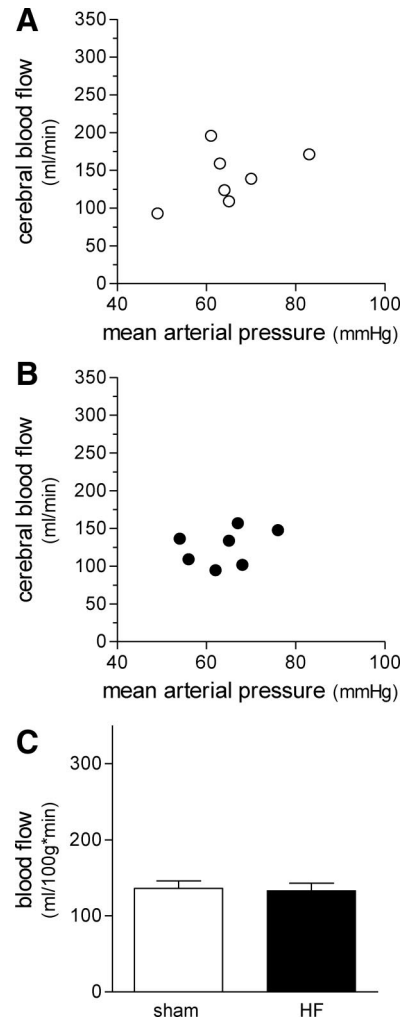


Figure 7. Heart failure (HF) does not alter cerebral blood flow or autoregulation in *Sphk1*^{-/-} mice. No correlation between mean arterial pressure and cerebral blood flow (CBF) was evident in **(A)** sham-operated *Sphk1*^{-/-} mice and **(B)** *Sphk1*^{-/-} mice with HF, indicating the presence of blood flow autoregulation. **C**, Global CBF was unaffected by HF in *Sphk1*^{-/-} mice. For both groups, $n=8$.

HF+etanercept, $228\pm 5 \text{ mL} \cdot 100 \text{ g}^{-1} \cdot \text{min}^{-1}$, $n=7$; $P<0.05$, HF versus sham or HF+etanercept; Table III in the online-only Data Supplement). However, this regimen also positively affected cardiac function (Table III in the online-only Data Supplement), making it difficult to attribute the positive outcome unambiguously to a vascular mechanism.

In subsequent experiments, etanercept treatment was initiated 6 weeks after LAD ligation (1 mg/mL sc twice per week for 2 weeks), under the premise that the heart injury would be more permanent at later time points following myocardial infarction. Indeed, this revised treatment regimen did not improve cardiac function (eg, CO, LVEF, stroke volume; Table IV in the online-only Data Supplement) but continued to restore CBF (Figure 8; representative flow-sensitive alternating inversion recovery-magnetic resonance imaging flow maps are displayed in Figure VI in the online-only Data Supplement).

Although both CO (inversely) and total peripheral resistance (positively) showed tight correlation with infarct size, MAP did not (Figure 8). Similarly, CBF was inversely

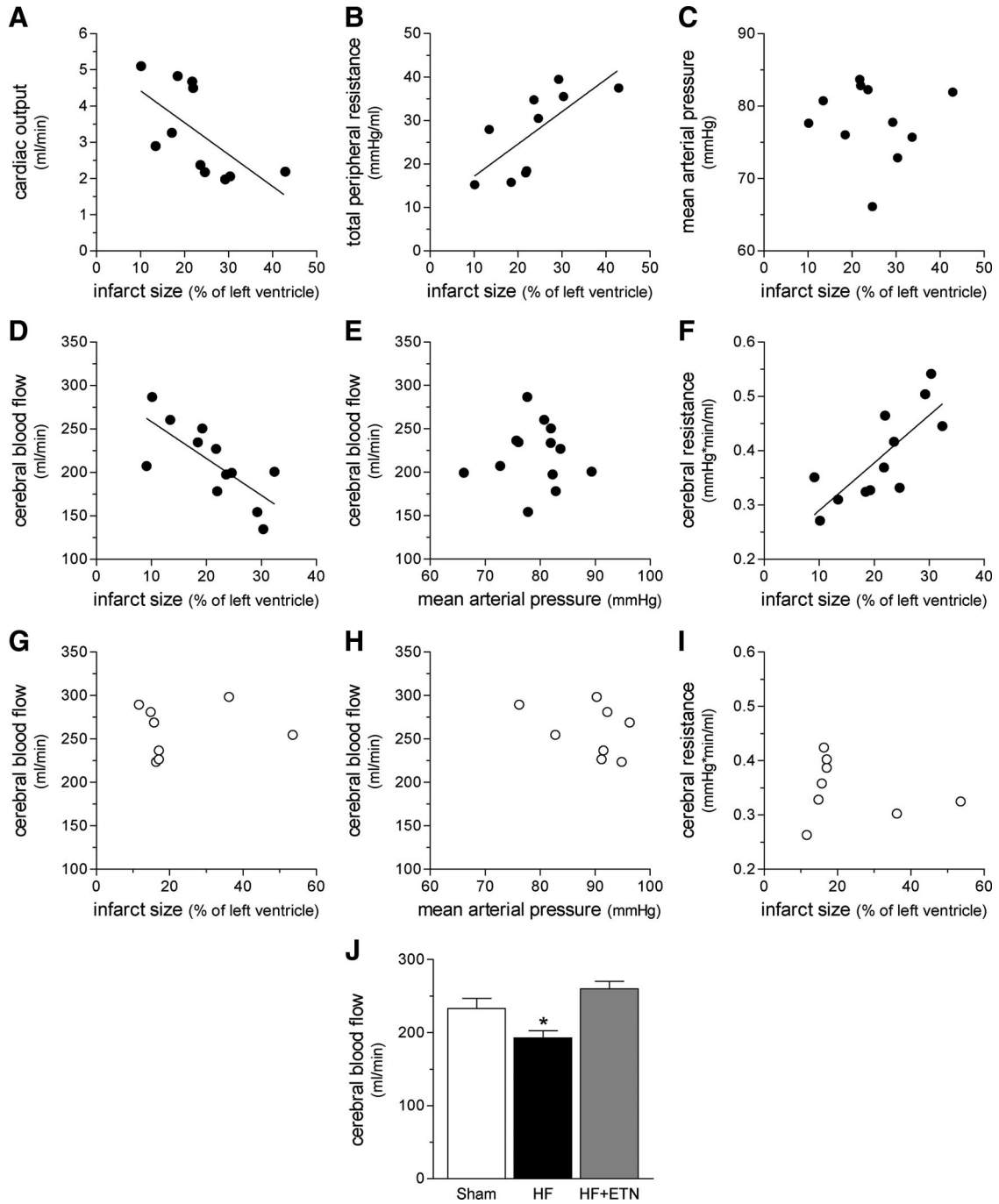


Figure 8. Correlation of systemic and cerebral hemodynamic parameters to infarct size. In heart failure (HF) mice (n=12), (A) cardiac output correlates inversely, (B) total peripheral resistance correlates positively, and (C) mean arterial pressure (MAP) does not correlate with infarct size. D, Cerebral blood flow (CBF) correlates inversely with infarct size but (E) does not correlate with MAP; instead, (F) the calculated values for cerebral resistance (MAP/CBF) positively correlate with infarct size. In contrast to saline-treated HF mice, (G) CBF does not correlate with infarct size in etanercept (ETN)-treated mice (initiated 6 weeks after left anterior descending ligation; n=8). Additionally, no correlations between (H) CBF and MAP or (I) cerebral resistance and infarct size are observed. J, Pooled data show that CBF in mice with HF (n=30) is ≈20% lower than in sham-operated controls (n=28); etanercept treatment normalizes CBF during heart failure (n=8). *P<0.05 vs all other groups.

correlated with infarct size but not MAP; instead, CBF was negatively correlated with calculated values for cerebral resistance (MAP/CBF). In contrast, etanercept-treated mice (6 weeks after LAD ligation; n=8) displayed no correlations between CBF and infarct size, CBF, and MAP or between cerebral resistance and infarct size.

Discussion

This investigation demonstrates that HF induces a widespread peripheral vascular response that includes an alteration in CBF autoregulation. In response to reduced CO, total peripheral resistance increases,^{29,30} which maintains MAP well within the acceptable range for blood flow autoregulation (ie,

60–150 mm Hg).⁸ This compensatory mechanism explains why MAP does not correlate with infarct size (Figure 8C).

Because MAP is maintained within the autoregulatory range, the observed reductions in CBF cannot be attributed to systemic hemodynamic parameters. The absence of a relationship between MAP and CBF in HF (Figure 8E) demonstrates that CBF autoregulation persists under these conditions, with reductions in CBF resulting from altered autoregulatory mechanisms within the cerebral microcirculation (ie, increased resistance at a given MAP). Together, these data suggest that HF induces a compensatory vascular response that serves to maintain MAP by elevating total peripheral resistance. CBF autoregulation is not exempted from this response. Indeed, the degree to which cerebral resistance increases is tightly correlated with the degree of heart injury (ie, infarct size; Figure 8F).

The reduction in CBF observed in this investigation is consistent with clinical reports in HF patients.^{1–4} Reduced perfusion of the brain would be expected to cause wide-ranging neurological effects; indeed, cognitive symptoms, including impairment of memory, attention, mental flexibility, and global cognitive functions, are clinically observed in 40% to 60% of patients with late-stage HF.^{1,2,31,32} The 25% CBF reduction observed in the present investigation, however, is below the reported threshold^{33–36} necessary to cause cognitive deficits or gross morphological changes and explains their absence in the present model.

In vitro, we confirm that a longitudinal gradient of myogenic activity exists within the cerebrovascular tree; proximal arteries display minimal myogenic tone, whereas the more distal sections possess substantial myogenic activity. Our results support the premise that proximal PCA branches do not play a primary role in adjusting CBF under normal physiological conditions. In HF, their phenotype changes: they display augmented myogenic tone that, under physiological conditions, is more characteristic of distal regions. In essence, myogenic reactivity and consequently microvascular resistance to blood flow extends to the proximal regions of the vascular tree, resulting in reduced cerebral blood supply.

The recruitment of PCAs into the myogenic chain results from an autocrine/paracrine effect of TNF α , which is released from PCA vascular wall. Although TNF α has a well-documented role in stroke³⁷ and HF,^{18,19} further studies are required to determine how HF actually activates TNF α in the PCA. Of note, we recently implicated TNF α -dependent signaling in the cochlear microcirculation as a pathogenic stimulus in sensorineuronal hearing loss.²³ The vascular effects of TNF α are generally attributed to increased serum levels of the cytokine; however, the present study demonstrates that HF induces an upregulation of TNF α mRNA and protein expression within the vascular wall of PCAs, with the vast majority of protein localized to the smooth muscle layer. We therefore propose that TNF α (or more specifically, the relevant pool of smooth muscle cell TNF α) acts in an autocrine/paracrine manner to enhance PCA smooth muscle cell contractility. This would explain why explanted PCAs retain their altered phenotype, characterized by augmented myogenic tone, over several hours ex vivo. Sequestering vessel wall TNF α with etanercept restores tone in HF PCAs

to sham levels, confirming that TNF α is causally involved in the tone-enhancing mechanism and that the vessel wall is the source of TNF α . Accordingly, exogenously applied TNF α induces the same phenotype shift in isolated proximal PCAs from naïve mice that was observed in HF mice (ie, from minimal to robust myogenic tone).

The molecular pathway that links TNF α to enhanced myogenic tone is the S1P signaling pathway. Consistent with our previous observations,¹⁴ S1P signaling is a key regulator of myogenic tone^{11–13} and is essential for the HF-mediated increase in proximal PCA myogenic tone. Using knockout models, we show that exogenous TNF α , a known activator of *Sphk1*,^{15–17} mediates its effects via *Sphk1* and *SIP₂R*. Specifically, isolated PCAs from mice lacking *Sphk1* (*Sphk1*^{-/-}), *Sphk1*, and 1 allele of *Sphk2* (*Sphk1*^{-/-}/*Sphk2*[±]) or *SIP₂R* (*SIP₂R*^{-/-}) do not have increased myogenic tone in response to TNF α .

The deletion of *Sphk1* abolishes the HF-induced augmentation of PCA myogenic tone (measured in vitro) and protects against HF-mediated reductions in CBF and changes in CBF autoregulation. Genetic deletion of *SIP₂R* also abolished the HF-induced augmentation of myogenic tone in isolated PCAs. JTE013 reverses both the TNF α - and HF-mediated increase in myogenic tone. Although JTE013 is a putative *SIP₂R* antagonist, we observed clear *SIP₂R*-independent effects (Figure VII in the online-only Data Supplement).³⁸ Nevertheless, JTE013 appears to retain specificity for S1P signaling (ie, does not inhibit endothelin-1 or phenylephrine responses),^{12,23} making it suitable for investigating the contributions of S1P receptors, despite an inability to discern the specific role of *SIP₂R*. Taken together, our data support that TNF α mediates its effects via S1P signaling, a conclusion that is further substantiated by our observation that TNF α sequestration (etanercept) is without effect in isolated PCAs with disrupted S1P signaling.

To therapeutically translate our in vitro data, we targeted TNF α in vivo with the clinically available agent etanercept. By delaying treatment to 6 weeks after LAD ligation, we mitigated the beneficial effects of etanercept on cardiac function (compare Tables II and III in the online-only Data Supplement). In the absence of improved cardiac function, we are able to unambiguously attribute the restored CBF to altered vascular function. We found that etanercept treatment broke the link between heart injury and cerebrovascular resistance/CBF (ie, eliminated the correlations observed in saline-treated HF mice; Figure 8). Importantly, we continued to observe no correlation between MAP and CBF in etanercept-treated mice with HF, indicating the normalization of autoregulation.

Significantly, although etanercept improved CBF autoregulation, it did not meaningfully alter total peripheral resistance (Table IV). This suggests that etanercept treatment acts selectively on certain microvascular beds during HF and positions the treatment as a possible strategy to discretely improve blood flow in critical organs (eg, the brain) during HF. Critical organ perfusion was not assessed in the Randomized Etanercept North American Strategy to Study Antagonism of Cytokines (RENAISSANCE) and Research Into Etanercept Cytokine Antagonism in Ventricular Dysfunction

(RECOVER) clinical trials, which were halted prematurely owing to a lack of beneficial effects on the end points of clinical composite score, HF hospitalization, and mortality.³⁹ Importantly, these trials also showed that etanercept did not worsen the clinical outcome of HF.³⁹ This finding encourages a reexamination of this pathway for the improvement or prevention of cerebral perfusion deficits in HF.

Conclusions

We demonstrate that TNF α recruits proximal cerebral arteries into a myogenic phenotype, resulting in comprised autoregulation and restricted CBF. We demonstrate that TNF α mediates the enhancement of PCA tone via Sphk1/S1P₂R signaling, all of which deserve evaluation as potential therapeutic targets for the improvement of CBF in HF patients. Indeed, our data show that the *in vivo* use of etanercept fully restores CBF in mice with HF. We propose that etanercept treatment restores the minimally restrictive phenotype of PCAs and shifts autoregulatory function back to the distal regions of the cerebral microcirculation.

Sources of Funding

We gratefully acknowledge the operating, infrastructure, and salary funding support from the Canadian Institutes of Health Research (Dr Bolz, FRN-84402 and FRN-119345; Dr Husain, FRN-117801), Canadian Foundation for Innovation (Dr Bolz, 11810), Ontario Research Fund (Dr Bolz, RI#11810; Dr Henkelman, RE#03-051, and RE#02-002), Canadian Stroke Network (Dr Bolz), Heart and Stroke Foundation of Ontario New Investigator Award (Dr Bolz, NI6581) and Career Investigator Award (Dr Husain, CI5503), and Canada Research Chair in Imaging Technologies in Human Disease and Preclinical Models (Dr Henkelman, 950-203746), as well as startup funding from the University of Toronto (Dr Bolz).

Disclosures

None.

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CLINICAL PERSPECTIVE

This study presents a novel concept, in which the cause of reduced cerebral blood flow in heart failure lies in the tumor necrosis factor- α - and sphingosine-1-phosphate-dependent recruitment of proximal cerebral arteries into the myogenic mechanism. Our investigation further identifies this pathophysiology as a therapeutic target. We illustrate that myogenic recruitment and consequent reductions in cerebral blood flow are reversed by tumor necrosis factor- α sequestration with etanercept, with additional benefits in cardiac function and peripheral resistance. These results challenge the notion that etanercept possesses limited usefulness for the treatment of heart failure and encourages a reevaluation using vascular and hemodynamic end points.