Leptomeningeal collaterals (LMCs) play a pivotal role in sustaining cerebral perfusion in patients with steno-occlusive disease of the internal carotid artery (ICA) and middle cerebral artery (MCA). Indeed, patients with inadequate LMC have increased stroke risk caused by hypoperfusion or impaired washout of thromboemboli. Consequently, structural and functional assessment of LMC is used to guide management decisions in these patients.

Digital subtraction angiography (DSA) remains the gold standard for determining LMC structure and anatomy despite its invasive nature. On the other hand, positron emission tomography and single-photon emission computed tomography or transcranial Doppler combined with a vasodilator have been used for functional assessment of LMC by measuring the autoregulatory capacity of cerebral blood flow or cerebrovascular reserve (CVR). Quantitative magnetic resonance angiography (QMRA) is another noninvasive technique that can be used to measure flow before and after Diamox challenge and has several advantages over the above methods, namely, flow changes are provided in all intracranial vessels without the use of radiotracers or ionizing contrast agents.

In this study, we examined the relationship between the degree of LMC and the flow change with Diamox challenge measured using QMRA.

**Methods**—Patients with steno-occlusion in the internal carotid artery or middle cerebral artery (MCA) at our institution between 2007 and 2013 were retrospectively studied. Intracranial flows were obtained using QMRA, and flow change with Diamox (QMRAΔd) was calculated as follows: ([flow after Diamox−flow before Diamox]/[flow before Diamox])×100%. Poor LMC was defined as grade 1 or 2, and robust LMC was defined as grade 3 or 4 based on the ASITN/SIR (American Society of Interventional and Therapeutic Neuroradiology/Society of Interventional Radiology) grading system on digital subtraction angiography.

**Results**—Thirty-eight patients had angiographic and flow data. Ipsilateral MCA QMRAΔd was significantly lower versus the contralateral side (flow, 85.5 versus 135.9 mL/min; P<0.001 and QMRAΔd, 24.0% versus 45.6%; P=0.01). If LMCs were robust (n=12), MCA QMRAΔd was significantly higher (21.4% versus −26.8%; P=0.04) compared with patients with poor LMC (n=4).

**Conclusions**—We show that patients with more robust LMC have better MCA QMRAΔd. Therefore, QMRAΔd may be used for the functional assessment of LMC as a surrogate for cerebrovascular reserve in chronic internal carotid artery or MCA steno-occlusive disease.

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Key Words: acetazolamide ◼ angiography, digital subtraction ◼ hemodynamics ◼ magnetic resonance angiography ◼ middle cerebral artery
LMC Grading
Collaterals were assessed with the ASITN/SIR (American Society of Interventional and Therapeutic Neuroradiology/Society of Interventional Radiology) grading system. These grades include 0=no LMCs visible to MCA territory, 1=slow LMCs to the periphery of MCA territory, 2=rapid LMCs to the periphery of MCA territory, 3=LMCs with slow but complete angiographic blood flow to MCA territory, and 4=complete and rapid LMCs to the MCA territory. Subsequently, collaterals were categorized as poor (grade 1 or 2) and robust (grade 3 or 4). We did not include patients with grade 0 or the absence of LMC in our binary scale as most of our subjects had ICA steno-occlusive disease, and the absence of LMC in these patients indicates robust primary collateral pathways that supply the MCA territory through anterograde flow.

Blood Flow Measurements Before and After Diamox
All patients underwent flow measurements of the extracranial and intracranial arteries before and after Diamox administration using QMRA. MCA flow change with Diamox (QMRA $\Delta d$) was calculated as follows: $(\text{flow after Diamox} - \text{flow before Diamox})/\text{flow before Diamox} \times 100\%$.

Statistical Analysis
Ipsilateral and contralateral MCA QMRA $\Delta d$ were compared using paired 2-tailed Student t-tests. Ipsilateral QMRA $\Delta d$ was compared between poor and robust LMC groups using independent 2-tailed Student t-tests. The relationship between QMRA $\Delta d$ and degree of LMC was assessed using Spearman correlation. Analyses were performed with SPSS (version 22; IBM, Inc).

Results
Patient Characteristics
Our cohort consisted of 38 patients with a mean age of 60 years. Mean percentage stenosis was 93% (range, 50%–100%), 90% had severe stenosis ≥70%, and 10% had moderate stenosis defined as 50% to 70%. Fifty-seven percent of LMC were grade 0, 2% grade 1, 8% grade 2, 2% grade 3, and 31% grade 4.

Relationship Between QMRA $\Delta d$ and Degree of LMC
Mean ipsilateral MCA QMRA $\Delta d$ was significantly impaired compared with the contralateral side (24.0% versus 45.6%; $P=0.01$). Among patients with poor LMC (n=4), mean MCA QMRA $\Delta d$ was significantly lower compared with the mean MCA QMRA $\Delta d$ in patients with robust LMC (n=12; −26.8% versus 21.4%; $P=0.04$; Figure 1). Spearman correlation between MCA QMRA $\Delta d$ and the degree of LMC demonstrated a positive but nonsignificant relationship ($\rho=+0.36$; $P=0.18$).

Discussion
This is the first study to investigate the relationship between flow changes with Diamox challenge (QMRA $\Delta d$) measured using QMRA and degree of LMC determined from DSA in patients with chronic ICA or MCA steno-occlusive disease. We showed that patients with robust LMC (grade 3 or 4) had significantly better MCA QMRA $\Delta d$ than patients with poor LMC (grade 1 or 2; 21.4% versus −26.8%; $P=0.04$). Illustrative cases are shown in Figures 2 and 3. Therefore, QMRA $\Delta d$ measured using QMRA with Diamox challenge may be used for the functional assessment of LMC and as a surrogate for CVR.

Robust collateral perfusion has been shown to compensate for compromised cerebral hemodynamics and has been linked to better CVR. Consequently, identification of patients with poor collateral flow and impaired CVR can guide treatment decision making in chronic steno-occlusive disease. Compared with existing modalities used to measure CVR, such as positron...
In this study, we examined the importance of functional status and grade of LMC in compensating for cerebral hemodynamic impairment instead of the presence of LMC alone. Indeed, we showed that robust rather than poor LMC is associated with higher QMRA Δd. We did not find a statistically significant correlation between all grades of LMC and MCA QMRA Δd, possibly because our patients were not equally distributed among different LMC subgroups.

**Study Limitations**

Our study is a retrospective review with a small sample size. In addition, patients were not distributed homogeneously across LMC subgroups. These limitations highlight the need for a larger prospective study on patients with different degrees of MCA or ICA stenosis with baseline QMRA Δd and LMC grade who are followed up over time for development of stroke.

**Conclusions**

We show that patients with more robust LMC have better MCA QMRA Δd. Therefore, QMRA Δd may be used for the functional assessment of LMC as a surrogate for CVR in chronic ICA or MCA steno-occlusive disease.

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**Disclosures**

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**Figure 3.** A–C, Illustrative case 2, patient with right internal carotid artery (ICA) occlusion and poor collateralization. A, Arterial phase of digital subtraction angiography (DSA) after left ICA injection displaying poor collateralization. B, Capillary phase of DSA after left ICA (LCA) injection displaying poor collateralization. C, Quantitative magnetic resonance angiography flow map with right middle cerebral artery (RMCA) flow change with Diamox measured as −11% (right box). BA indicates basilar artery; LACA, left anterior cerebral artery; LMCA, left middle cerebral artery; LPCA, left posterior cerebral artery; LVA, left vertebral artery; RACA, right anterior cerebral artery; RPCA, right posterior cerebral artery; and RVA, right vertebral artery.
Angiographic Correlates of Cerebral Hemodynamic Changes With Diamox Challenge Assessed by Quantitative Magnetic Resonance Angiography
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