Introduction

Stroke is a leading cause of morbidity and mortality, whose prevalence increases dramatically with age. Despite its substantial heritable basis, only a small number of causative genes have so far been identified, generally for severe early-onset phenotypes (cerebral autosomal dominant or recessive arteriopathy with subcortical infarcts and leukoencephalopathy: CADASIL, NOTCH3, CARASIL, HTRA1, and porencephaly (COL4A1)) (1–3). Such cases have revealed important pathways that contribute to stroke, including the roles of Notch and TGF-β signaling. In the same way, the vascular basement membrane’s contribution (COL4A1 and COL4A2) (3, 4) to juvenile stroke phenotypes further stimulated investigation of the cellular components (endothelial and mural cells) upon which brain vascular integrity depends. The demonstration that Notch signaling regulates pericyte numbers (5, 6) has in turn provided a mechanistic explanation for disorders such as CADASIL. These examples of juvenile stroke resulting from severe alterations in brain vascular development raise the intriguing possibility that milder changes contribute to late-onset disease and that a larger proportion of strokes have embryonic origins. It is therefore notable that the same genes regulate cerebral structural development and angiogenesis (7) and that the cell populations essential for cerebral vascular homeostasis (pericytes and vascular smooth muscle) are predominantly derived from the neural crest (8, 9).

The increasing prevalence of stroke exerts disproportionately severe effects on the quality of life of affected individuals and their families. Consequently, phenotypes predictive of future stroke merit investigation, with the goal of developing treatments targeting causative pathways and preventing a frequently preterminal disease. One such phenotype is cerebral small-vessel disease (CSVD), which represents a major risk factor for both ischemic and hemorrhagic stroke (10–13). Characterized by perturbed perforating end-artery function, CSVD results in lesions apparent on MRI that encompass white matter hyperintensities (WMHs), dilated perivascular spaces, microbleeds, and lacunar infarcts. These markers of cerebrovascular pathology provide opportunities for gene discovery and for defining the mechanisms that contribute to subsequent stroke.

Our study evaluated the hypothesis that the forkhead box transcription factor FOXC1, which patterns multiple organs including the CNS, contributes to CSVD. It was prompted by a higher incidence of self-reported stroke in some of our local pedigrees with FOXC1 mutations and supported experimentally by: (a) blood-stained hydrocephalus in murine Foxc1−/− mutants, (b) related zebrafish foxc1 morphant phenotypes, and (c) the exten-
Genomic Epidemiology (CHARGE) consortium. This identified 10 WMH-associated SNPs ($P = 0.0031–0.048$, Bonferroni-corrected) located in an intron of \textit{GMDS}, which catalyzes GDP-mannose metabolism and lies adjacent to \textit{FOXC1} (Figure 1A and Supplemental Table 1; supplemental material available online with this article; doi:10.1172/JCI75109DS1). Analysis of 2 independent expression quantitative trait loci (eQTL) datasets (19, 20) demonstrated that 3 of these WMH-associated SNPs strongly influence \textit{FOXC1} transcript levels (study 1: $P = 2.96 \times 10^{-8}–5.82 \times 10^{-11}$; study 2: $P = 0.01–0.008$; Supplemental Table 1).

We next assessed whether patients with \textit{FOXC1}-attributable ARS exhibited CSVD. Eighteen patients with either a \textit{FOXC1} mutation or copy number variation (CNV) (comprising missense

sive involvement of Foxc1 in vascular development (14–16). The latter encompasses essential roles in arterial specification, angiogenesis regulation, endothelial lymphatic cell sprouting (17), as well as a requirement for Foxc1 in brain pericytes (18). Here, we demonstrate a role for FOXC1 in cerebrovascular disease through targeted genome-wide association (GWA) analysis, MRI of glaucoma patients with \textit{FOXC1}-attributable Axenfeld-Rieger syndrome (ARS), and detailed zebrafish analyses.

Results and Discussion
We first performed a meta-analysis of GWA data for 500 kb encompassing \textit{FOXC1} on 6p25 in 9,361 individuals with brain MRI data from the Cohorts for Heart and Aging Research in

Figure 1. Aberrant \textit{FOXC1} function causes CSVD in patients and cerebral hemorrhage in zebrafish. (A) Regional association plot (meta-analysis, CHARGE consortium) displaying linkage disequilibrium between the 10 SNPs with WMH. (B) Diagrammatic representation of the missense or nonsense \textit{FOXCl} mutations or CNV extent for the 18 patients imaged. (C–H) MRIs of patients with \textit{FOXCl} mutation (C–F), 6p25 deletion (G), and 6p25 duplication (H) displaying WMH (arrow), dilated perivascular spaces (arrowhead), and lacunar infarct (asterisk). (I and J) Injection of 2 ng of foxcla morpholino (MO) and 2 ng of foxclb morpholino resulted in cerebral hemorrhage (arrow) at 48 hpf compared with injection of equimolar amounts of 5-bp mismatched morpholinos. Overexpression of foxcl1a mRNA (75 pg) caused cerebral hemorrhage (K). Scale bars: 200 $\mu$m.
Figure 2. Foxc1 regulates Pdgf signaling. Transcripts for pdgfra (Pdgfra) and pdgfrb (Pdgfrb) were expressed in neural crest cells at 20 hpf (arrows) in WT embryos (A and C) and were highly downregulated in foxc1 morphants (B and D). At 48 hpf, expression of pdgfra was observed in major cerebral blood vessels and ventral head mesenchyme (E, arrow), with the latter being reduced in foxc1 morphants (F), whereas pdgfrb expression was unaltered (G and H). A genetic interaction was observed between subthreshold inhibition of foxc1 and pdgfra (I) or with treatments that affected both Pdgfra and Pdgfrb signaling, including dual-morpholino suppression (K) and the pan-Pdgf inhibitor crenolanib (L). No interaction was observed using subthreshold inhibition of foxc1 and pdgfrb alone (J). Scale bar: 200 μm.

[n = 4] or frameshift mutation [n = 3], segmental deletion [n = 5], or duplication [n = 6]) (Figure 1B) were recruited for cerebral MRI (Supplemental Table 2). All 18 displayed CSVD, including WMH, dilated perivascular spaces, and lacunar infarcts (Figure 1, C–H, Supplemental Figure 1, and Supplemental Table 2). These changes, present in patients as young as 1 year of age, reveal a development component to CSVD. Cerebrovascular phenotypes were evident with both 6p25 segmental duplication or deletion, demonstrating that deviations from normal FOXC1 gene dosage result in similar anomalies, as previously observed with FOXC1-dependent cerebellar maldevelopment (21), corneal neovascularization (22), and ARS (23, 24). The 7 patients with coding mutations unambiguously demonstrate that impaired FOXC1 function alone is sufficient to induce CSVD.

Consistent with these data, overexpression of zebrafish foxc1a or dual suppression of both paralogs (foxc1a and foxc1b) results in cerebral hemorrhage (overexpression 32 of 111 [28.8%], suppression 111 of 352 [31.5%]; Figure 1, I–K, and Supplemental Table 3). Notably, acellular perivascular spaces were evident on electron microscopy of foxc1 morpholino oligonucleotide–treated embryos (foxc1 morphants) (Supplemental Figure 2). Foxc1 was expressed in the neural crest, and in morphants, there was aberrant migration of the cerebral neural crest from which most mural cells are derived (Supplemental Figures 3 and 4). Since platelet-derived growth factor (PDGF) signaling regulates neural crest recruitment to the developing vasculature, we evaluated this candidate pathway in foxc1 morphants. We observed reduced expression of both receptor tyrosine kinases (pdgfra and pdgfrb) in foxc1 morphants (Figure 2, A–H), positioning Pdgf signaling genetically downstream of Foxc1. Importantly, the prevalence of cerebral hemorrhage induced by morpholino inhibition of pdgfra alone, or pharmacological inhibition of pdgfra and pdgfrb, synergized with foxc1 morpholino inhibition (Figure 2, I–L). This is consistent with a model in which Foxc1 regulates vascular stability through the Pdgfra homodimer and Pdgfrb heterodimer, either by the control of pdgfra and pdgfrb expression or indirectly as a consequence of aberrant neural crest migration and/or survival.

Since loss of neural crest–specific Pdgf induces murine cerebral hemorrhage and irregular vascular smooth muscle cell coverage (25, 26), we predicted loss of such cells in foxc1 morphants. In keeping with the aberrant cerebral neural crest migration and increased cell death (Supplemental Figure 4), foxc1 morphants exhibited reduced numbers of neural crest cells associating with the cerebral vasculature at 32 hours post fertilization (hpf) (foxc1MO 48 ± 10, WT 61 ± 9; P = 0.0008) (Figure 3, A–C). Consistently, at 4 days post fertilization (dpf), this manifested as reduced numbers of vascular smooth muscle cells (foxc1MO 48 ± 10, WT 61 ± 9; P = 0.01) (Figure 3, D–F). In contrast, we found that expression of markers for other vascular components (col4a1 and claudin5b) and endothelial cell numbers in both morphants and murine endothelial–specific FoxC1–/– mutants was unaltered (Supplemental Figure 5). Together, these data support a model of reduced neural crest–derived smooth
muscle cell coverage, impairing vascular stability (27), as a key component of foxc1 morphants' hemorrhagic phenotype.

To test the hypothesis that other ocular developmental genes with neural crest roles contribute to CSVD, we analyzed regional GWA data for PITX2, a neural crest–expressed, ARS-causing transcription factor that physically interacts with FOXC1. PITX2 is associated with atrial fibrillation (28) and cardioembolic stroke (29), with the latter attributed to cardiac arrhythmia. Nine SNPs within a 500-kb PITX2-encompassing interval were significantly associated with WMH ($P=0.0071–0.022$, Bonferroni-corrected; Supplemental Table 4 and Supplemental Figure 6, and MRIs of young PITX2-attributable ARS patients revealed CSVD (Figure 3, G and H). Thus, PITX2 may increase stroke risk independently of atrial fibrillation. Consistent with such a primary alteration to cerebral vasculature, murine Pitx2−/− mutants exhibited reduced and discontinuous smooth muscle actin staining of cerebral vessels (Figure 3, I and J) as well as increased cerebral vessel density (Pitx2−/− $12.2 ± 0.8$, WT $9.3 ± 1.0$; $P=0.04$).

By demonstrating that aberrant FOXC1 function causes human cerebrovascular disease, this study extends the knowledge of disorders whose genetic etiology remains largely unexplained. Our data from patients and zebrafish models, coupled with another laboratory’s detailed analysis of murine Foxc1 mutants (18), reveal the contribution from altered neural crest function and substantially increase the proportion of strokes known to have developmental origins. Furthermore, the evidence presented here from Foxc1 and Pitx2 implicates other transcription factors with neural crest roles as candidates and thus provides practical opportunities for accelerating the identification of the molecular basis for stroke through integrated human genetic and zebrafish analyses. Our observation of a predominantly mural role for Foxc1 in the cerebral vasculature, which contrasts with an endothelial cell contribution systemically (16), also merits investigation and may correlate with the unique endothelial barrier properties of the cerebral circulation. From a clinical perspective, the substantial interval that elapses between the onset of MRI-detectable features of CSVD and the occurrence of stroke provides a therapeutic window for intervention, and potentially, patients with mutations involving neural crest genes may benefit from common stroke-prevention strategies. Finally, our findings have direct implications for Axenfeld-Rieger syndrome, a glaucoma subtype frequently associated with progressive visual decline despite surgical control of intraocular pressure (30). Evidence of a cerebral vasculopathy raises the possibility that perturbed vascular function contributes to the visual loss that has previously been attributed to optic nerve disease.

Figure 3. foxc1 and PITX2 regulate vascular smooth muscle cell numbers. Number of sox10-positive neural crest cells that associated with the cerebral vasculature in WT embryos at 32 hpf (A) was significantly reduced in foxc1 morphants (B and C). Cerebral vascular mural cells expressed smooth muscle actin by 4 dpf (D), with fewer smooth muscle actin-positive cells observed in foxc1 morphants (E and F). Patients with PITX2-attributable ARS exhibited CSVD. (G) WMH, (arrows) and (H) dilated perivascular spaces (arrowheads). Compared with WT embryos (I), murine Pitx2−/− mutants demonstrated reduced and discontinuous smooth muscle actin staining of large and small cerebral vessels (J). Original magnification, ×200 (A and B), ×100 (D and E), and ×400 (I and J).
Methods
Statistics. GWA data are presented as the $-\log_{10}$ value, with Bonferroni’s correction for the number of independent comparisons determined via the number of linkage disequilibrium blocks. For analysis of cell numbers and genetic interactions, unpaired 2-tailed Student’s t tests were used to assess significance. Analyses are displayed graphically as the mean ± SEM. All experiments were conducted in triplicate. A $P$ value of less than 0.05 was considered statistically significant.

Study approval. Ethical approval was provided by the University of Alberta Health Research Ethics Board, with written informed consent received from all participants prior to their inclusion in the study. Animal experiments were approved by the IACUC of the University of Alberta, the University of Michigan, and Northwestern University.

Further details regarding the methods are available in the Supplemental Methods.

Acknowledgments
We are grateful to the patients who participated in this study. We thank Brian Link (Medical College of Wisconsin), Michael Walter (University of Alberta), Peter Carlsson (University of Gothenburg), and Alison Hardcastle (Institute of Ophthalmology, United Kingdom) for very helpful advice and reagents; Peter Seres and colleagues at the Peter S. Allen MR Research Centre for MR imaging; Aleah McCorry for zebrasfish husbandry; and Wei Dong and the University of Calgary Microscopy and Imaging Facility for help with transmission electron microscopy. Funding was provided by National Eye Institute/NIH grants EY014126 and EY007003 (to P.J. Gage) and RO1 EY019484 (to T. Kume); the Canadian Institutes of Health Research (CIHR) (MOP-133568, to O.J. Lehmann and MOP-114902, to S.J. Childs); the Natural Sciences and Engineering Research Council (to A.J. Waskiewicz); and a Heart and Stroke Foundation of Canada postdoctoral fellowship (to C.R. French). C.R. French is the recipient of an American Society of Human Genetics Charles Epstein Trainee Award. C.R. Arnold is the recipient of a CIHR Training Grant in Genetics, Child Health and Development studentship.

Address correspondence to: Ordan J. Lehmann, Departments of Ophthalmology and Medical Genetics, 829 Medical Sciences Building, University of Alberta, Edmonton, AB T6G 2H7, Canada. Phone: 001.780.492.8550; E-mail: olehmann@ualberta.ca.