Ezh2-mediated repression of a transcriptional pathway upstream of Mmp9 maintains integrity of the developing vasculature

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ABSTRACT

Maintenance of vascular integrity is required for embryogenesis and organ homeostasis. However, the gene expression programs that stabilize blood vessels are poorly understood. Here, we show that the histone methyltransferase Ezh2 maintains integrity of the developing vasculature by repressing a transcriptional program that activates expression of Mmp9. Inactivation of Ezh2 in developing mouse endothelium caused embryonic lethality with compromised vascular integrity and increased extracellular matrix degradation. Genome-wide approaches showed that Ezh2 targets Mmp9 and its activators Fosl1 and Klf5. In addition, we uncovered Creb3l1 as an Ezh2 target that directly activates Mmp9 gene expression in the endothelium. Furthermore, genetic inactivation of Mmp9 rescued vascular integrity defects in Ezh2-deficient embryos. Thus, epigenetic repression of Creb3l1, Fosl1, Klf5 and Mmp9 by Ezh2 in endothelial cells maintains the integrity of the developing vasculature, potentially linking this transcriptional network to diseases with compromised vascular integrity.

KEY WORDS: Ezh2, Epigenetics, Histone methylation, Vascular development, Vascular stability, Endothelium, Extracellular matrix, Mmp9, Mouse

INTRODUCTION

Stability of the vasculature is essential for embryonic development and tissue homeostasis. Although the establishment of vascular cell fate, differentiation, and new vessel formation has been extensively investigated, the mechanisms that stabilize the developing vasculature are less understood. Endothelial extracellular matrix (ECM) homeostasis is key for vascular stability during development (Ingram et al., 2013), as the ECM provides a scaffold that supports the organization of endothelial cells into blood vessels (Davis and Senger, 2005), and its degradation by increased activity of matrix metalloproteinases (MMPs) compromises embryonic development (Chang et al., 2006) and cardiovascular function (Spinale et al., 2013). Mmp9 is an important regulator of ECM homeostasis in development and disease. Increased activity of Mmp9 compromises vascular integrity in cardiovascular pathologies including aortic aneurysm (Duellman et al., 2012; Longo et al., 2002), and can promote rupture of atherosclerotic plaques (Gough et al., 2006). Thus, Mmp9 expression must be kept in check to maintain vascular integrity.

Gene expression programs are stabilized by repressive histone methylation (Black et al., 2012), which is required for long-term organ homeostasis (Delgado-Olguín et al., 2012). The polycomb repressive complex 2 (PRC2), which tri-methylates lysine 27 of histone H3 (H3K27me3) through Ezh2, regulates angiogenesis and has been indirectly associated with Mmp9 expression. Ezh2 promotes angiogenesis in ovarian carcinoma (Lu et al., 2007, 2010) and glioblastoma cells (Smits et al., 2011, 2010). In human umbilical vein endothelial cells (HUVECs), Ezh2 also promotes angiogenesis by regulating cell adhesion and communication (Dreger et al., 2011). By contrast, Ezh2 inhibits endothelial differentiation and angiogenesis in vitro in Ewing tumor cells (Richter et al., 2009). In addition, Ezh2-mediated repression of tissue inhibitors of metalloproteinases (TIMPs) indirectly promotes Mmp9 activity in prostate cancer cells (Shin and Kim, 2012). Mmp9 is epigenetically regulated by DNA methylation and histone acetylation in cancer cells (Labrie and St-Pierre, 2013). However, whether Ezh2 controls the expression of Mmp9 or its transcriptional activators in developing endothelium, or whether Ezh2 has a function in vascular development and maintenance are unknown.

Transcriptional activators of Mmp9 in non-endothelial cells include the leucine zipper protein FOS-like antigen 1 (Fosl1) (Kent et al., 2011), the zinc-finger protein Kruppel-like factor 5 (Klf5) (Shinoda et al., 2008) and cAMP response element-binding protein (Creb). Fosl1 activates Mmp9 expression in trophoblasts, Klf5 in cartilage and Creb in mesothelial cells (Shukla et al., 2009). In addition, Klf5 is linked to vascular inflammation (Lu et al., 2013), aortic aneurysm and heart failure (Haldar et al., 2010), and Creb enhances inflammation in a model of atherosclerosis (Kotla et al., 2013), suggesting functions in vascular maintenance. However, whether Fosl1, Klf5 or Creb-like proteins are regulated in endothelial cells, or whether they are involved in the maintenance of the developing vasculature, is unknown. Uncovering key regulators of Mmp9 in endothelial cells could provide insight into vasculature development and maintenance, and into the mechanisms of cardiovascular disease.

RESULTS

Ezh2 is required for vascular integrity

Ezh2 was inactivated in developing endothelial progenitor cells via Tie2::cre-mediated homologous recombination. Efficient Ezh2
inactivation was revealed by significantly decreased H3K27me3 immunofluorescence signal in Pecam-expressing cells of E10.5 embryos (supplementary material Fig. S1). High-throughput sequencing of RNA (RNA-seq) revealed higher expression of Ezh2 than Ezh1 (22.48 versus 2.92 fragments per kilobase of exon per million fragments mapped, or FPKM) in sorted endothelial cells, and the expression of Ezh1 did not change upon Ezh2 deletion (P > 0.5), indicating that Ezh2 is the major H3K27me3 methyltransferase in developing endothelial cells. Overall normal vascular patterning in Ezh2 mutants, as shown by whole-mount immunostaining of Pecam on E10.5 embryos (supplementary material Fig. S2), suggests that Ezh2 is not crucial for endothelial cell differentiation in the developing vasculature. However, homozygous mutant embryos died between E13.5 and E14.5 (supplementary material Table S1), indicating an essential function for endothelial Ezh2 in the later stages of vascular development.

Consistent with the involvement of Ezh2 in erythropoiesis in the developing liver (Mochizuki-Kashio et al., 2011), Ezh2 mutant embryos appeared anemic (Fig. 1; supplementary material Fig. S3A). In addition, E11.0 mutant embryos had abnormal endocardial arrangement, with a gap present between the endocardium and myocardium (supplementary material Fig. S3B). At E12.5, embryos appeared anemic and had internal hemorrhaging, with extravasated red blood cells in the mesenchyme surrounding the brachial plexus (Fig. 1A,B). Furthermore, electron microscopy revealed gaps in the endothelium lining the brachial plexus (Fig. 1C). At E13.5, 83% of mutant embryos had superficial hemorrhages (Fig. 1D) and a thinner ventricular wall (supplementary material Fig. S3C,D). In addition, internal hemorrhaging was present, with extravasated red blood cells surrounding the external jugular vein (Fig. 1D,E). E14 mutant embryos died of severe superficial hemorrhaging and had extravasated red blood cells surrounding the brachial plexus (Fig. 1F,G). Immunostaining for phosphorylated histone H3 and activated caspase 3 in Pecam-expressing endothelial cells was comparable between control and mutant embryos (supplementary material Fig. S4), suggesting that Ezh2 deficiency does not affect endothelial cell proliferation or induce apoptosis. Thus, Ezh2 is required for the maintenance of vascular integrity during development.

**Ezh2 represses regulators of ECM remodeling in developing endothelium**

As a first approach to uncover the mechanistic involvement of Ezh2 in vascular integrity, we analyzed the global gene expression pattern of endothelial cells sorted from E10.5 mouse embryos. At this developmental time-point, the vascular integrity defects are not yet apparent in Ezh2 endothelial-specific knockouts. Endothelial cells were genetically labeled by crossing ROSA26mT/mG transgenic mice, which have a reporter driving constitutive expression of membrane Tomato and a Cre-inducible membrane GFP (Muzumdar et al., 2007), with Tie2::cre mice. Ezh2 WT females were crossed with Ezh2WT::Tie2::cre; ROSA26mT/mG males to obtain control Ezh2WT; Tie2::cre; ROSA26mT/mG and mutant Ezh2WT::Tie2::cre; ROSA26mT/mG embryos. To exclude the effect of Ezh2 deletion on erythropoiesis, the liver primordium was dissected out (supplementary material Fig. S5A) before disassociation of embryos. The GFP-positive cell population sorted from Ezh2 mutants (supplementary material Fig. S5B) efficiently deleted Ezh2 and had decreased levels of Ezh2 mRNA, as shown by RT-PCR and real-time quantitative PCR (qPCR), Fig. 1. Ezh2 is essential for vascular integrity. (A) Control (Ezh2WT) and mutant (Ezh2WT::Tie2::cre) embryos at embryonic day 12.5 (E12.5). Mutant embryos appear anemic when compared with controls. (B) Higher magnification section of the brachial plexus (BP) showing extravasated blood cells (arrows). (C) Transmission electron micrograph showing a disrupted cellular junction (arrows) in mutant (Ezh2WT::Tie2::cre), but not control (Ezh2WT), embryos. (D-F) Whole-mount control and mutant embryos at E13.5 and 14.0, respectively, showing hemorrhages (arrows). (E,G) Higher magnification sections of the external jugular vein (EJV) and brachial plexus (BP) of E13.5 and E14.0 embryos, respectively, showing extravasated red blood cells (arrows). Scale bars: 200 μm in A,B,D-G; 1 μm in C.
respectively (supplementary material Fig. S5C,D). In addition, the endothelial markers Flk1 and Pecam were enriched in the sorted cell population when compared with whole embryos (supplementary material Fig. S5E), indicating that the isolated cell population is enriched in endothelial cells. RNA-seq analysis revealed that Ezh2-deficient endothelial cells misregulated 1084 genes, of which 858 were upregulated and 226 downregulated (Fig. 2A; supplementary material Table S2). Functional annotation of the upregulated genes using DAVID (Huang et al., 2009a,b) revealed enriched gene ontology categories related to cell adhesion and ECM remodeling (supplementary material Fig. S6), suggesting potentially altered functions leading to instability of the Ezh2-deficient endothelial cell layer. Indeed, Mmp9, an important mediator of ECM degradation in normal physiology and diseases associated with compromised vascular integrity (Duellman et al., 2012; Gough et al., 2006; Longo et al., 2002), was upregulated. Furthermore, Fosl1 and Klf5, known Mmp9 activators in non-endothelial contexts (Kent et al., 2011; Shinoda et al., 2008; Shukla et al., 2009), and the transcription factor cAMP-responsive element binding protein 3-like 1, or Creb3l1, were also upregulated (Fig. 2A; supplementary material Table S2).

To identify direct targets of Ezh2 function, we immunoprecipitated H3K27me3-enriched chromatin followed by high-throughput sequencing (ChIP-seq). Chromatin was immunoprecipitated from endothelial GFP-positive cells sorted from E10.5 Ezh2^+/+;Tie2::cre; ROSA26^mT/mG embryos. ChIP-seq identified 3575 genes marked with H3K27me3. Such genes include previously identified targets of PRC2 in other contexts such as the pluripotency regulator Sox2, Hox genes and the homeodomain transcription factor Six1 (Boyer et al., 2006; Delgado-Olguin et al., 2012) (supplementary material Fig. S7 and Table S2). Overall, H3K27me3-marked genes tended to be expressed at lower levels in both control and Ezh2-deficient cells when compared with genes lacking H3K27me3 (supplementary material Fig. S8A). In addition, the analysis revealed that genes marked by H3K27me3 were not predisposed towards differential expression in Ezh2-deficient endothelial cells (supplementary material Fig. S8B). However, a subset of 231 genes marked with H3K27me3 was significantly upregulated, and only 29 genes were downregulated (Fig. 2A, supplementary material Table S2). H3K27me3-marked upregulated genes include those involved in ECM remodeling identified by functional annotation (Fig. 2A,B). Furthermore, Fosl1, Klf5 and Creb3l1, which were strongly activated in Ezh2-deficient endothelial cells, were identified as direct Ezh2 targets (Fig. 2B; supplementary material Table S2). However, CCAAT/enhancer-binding protein ε (Cebpe) was not marked by H3K27me3. Thus, Ezh2 appears to repress a transcriptional pathway that promotes ECM degradation and disrupts integrity of the developing vasculature.

**Ezh2-deficient endothelium has increased gelatinase/collagenase activity and upregulates Mmp9 activators**

Upregulation of Mmp9 and its transcriptional activators suggests that Ezh2-deficient endothelium may have increased extracellular matrix degradation. To test this hypothesis, we first assessed the distribution of Mmp9 in wild-type and Ezh2-deficient endothelium in sections of E11.0 embryos by immunofluorescence. Mmp9 was detected in the cytoplasm of endothelial cells of mutant, but not control, embryos (Fig. 3A). ECM degradation was assessed by *in situ* zymography, which detects gelatinase/collagenase activity, on sections of E11.0 embryos. Activity was detected in the Ezh2-deficient endothelial cell layer that lines the jugular vein, but not the normal endothelium (Fig. 3B). Preincubating the tissue sections with a metalloprotease inhibitor blocked gelatinase/collagenase activity in Ezh2-deficient endothelium (Fig. 3B). These results suggest increased ECM remodeling in Ezh2-deficient endothelium.

To confirm that Klf5, Fosl1 and Creb3l1 are induced at the protein level in Ezh2-deficient endothelium, we assessed their expression by *in situ* hybridization (supplementary material Fig. S9). It is possible that Klf5, Fosl1 and Creb3l1 activate Mmp9 gene expression when derepressed in Ezh2-deficient endothelial cells.

**Creb3l1 induces endogenous expression of Mmp9 in endothelial cells**

To understand the basis for transcriptional activation of Mmp9 in Ezh2-deficient endothelial cells, we analyzed the Mmp9 promoter...
looking for conserved transcription factor-binding motifs. rVista (Loots and Ovcharenko, 2004) identified conserved SP1- and AP1-binding motifs, which are recognized by Klf5 and Fosl1, respectively, in mouse and human. In addition, binding motifs for CREB and CEBP were also conserved (Fig. 4A). Creb3l1 and Cebpe were among the most significantly upregulated genes in Ezh2-deficient endothelial cells, and Fosl1 and Klf5 were also highly upregulated (Fig. 2A). Therefore, we addressed the ability of Creb3l1, Fosl1, Klf5 and Cebpe to activate Mmp9 gene expression in endothelial cells. cDNAs encoding these transcription factors were overexpressed in bovine aortic endothelial cells (BAECs), in which we measured endogenous Mmp9 by qPCR and protein levels by western blot. The transfected factors were highly expressed, as confirmed by qPCR (data not shown). Cebpe, which is not targeted by Ezh2 (Fig. 2), did not induce Mmp9 expression. By contrast, Creb3l1, Fosl1 and Klf5, which are direct Ezh2 targets (Fig. 2), robustly induced Mmp9 expression (Fig. 4B). Increased Mmp9 protein levels were also observed (Fig. 4C).

**Creb3l1 directly activates the Mmp9 promoter in endothelial cells**

To test the capacity of Creb3l1, Fosl1 and Klf5 to directly activate the expression of Mmp9 directly we analyzed the induction of luciferase reporters driven by the mouse and human Mmp9 and MMP9 proximal promoters, which include conserved Creb, Fosl and Klf-binding motifs (Fig. 4A; supplementary material Fig. S10). Creb3l1, but not Klf5 or Fosl1, activated both the human and mouse proximal promoters in BAECs (Fig. 4D; supplementary material Fig. S10). It is possible that functional Fosl1- and Klf5-responsive elements are located distal to the proximal promoter. Mutation of the Creb- but not the Klf-binding motif in the human and mouse Mmp9 and MMP9 promoter significantly decreased activity (Fig. 4D; supplementary material Fig. S10). Furthermore, chromatin immunoprecipitation revealed interaction of Creb3l1 concomitant with increased PolII recruitment on the Mmp9 promoter in BAECs transfected with Creb3l1 cDNA (Fig. 4E). Thus, Ezh2 represses Mmp9 as well as Creb3l1, which directly activates Mmp9 promoter activity in endothelial cells via its conserved binding site (Fig. 4F).

**De-repression of Mmp9 causes vasculature instability in Ezh2-deficient endothelial cells**

To test the involvement of de-repression of Mmp9 in vascular instability caused by Ezh2 deficiency, we genetically inactivated Mmp9 in Ezh2flo/+;Tie2::cre embryos by crossing Ezh2flo/+;Tie2::cre;Mmp9+/- males with Ezh2flo/flo;Mmp9-/- females. These crosses produced 19% live Ezh2flo/flo;Tie2::cre;Mmp9+-/+ embryos (as determined by presence of a heartbeat) at E13.5, which is closer to the 25% expected, than the 8% live Ezh2flo/flo;Tie2::cre embryos recovered at the same stage (supplementary material Table S1). Although 7%, of the expected 12.5% of live Ezh2flo/flo;Tie2::cre;Mmp9+-/- embryos were recovered (supplementary material Table S3), none of these Ezh2flo/flo;Tie2::cre;Mmp9+-/- embryos presented superficial or internal hemorrhages (Fig. 5A,B; supplementary material Table S3; P<0.001 by Fisher’s exact test). In addition, although 83% of Ezh2flo/flo;Tie2::cre embryos were hemorrhagic, only 37% of Ezh2flo/flo;Tie2::cre;Mmp9+-/- embryos had hemorrhages.
Furthermore, the disorganization of the smooth muscle cell layer and endothelial cell detachment observed in Ezh2fl/fl;Tie2::cre embryos at E12.5 were rescued in Ezh2fl/fl;Tie2::cre;Mmp9−/− embryos (Fig. 5C).

Altogether, our results suggest that Ezh2 represses the expression of Mmp9 and its transcriptional activators in developing endothelial cells to limit ECM remodeling, thus promoting vascular stability during embryogenesis.

**DISCUSSION**

Regulation of endothelial ECM remodeling during development is essential for embryogenesis (Lu et al., 2011), but the transcriptional mechanisms involved are poorly understood. We found that Ezh2 stabilizes the developing vasculature by repressing a transcriptional pathway that activates Mmp9 (Fig. 4F). Other chromatin modifiers such as the histone deacetylase HDAC7 (Chang et al., 2006), the ATP-dependent chromatin remodeler BRG1 (Davis et al., 2013) and the chromodomain-helicase-DNA-binding protein 4, or CHD4, which is an ATPase of the nucleosome-remodeling and histone deacetylase (NuRD) chromatin-remodeling complex (Ingram et al., 2013), function in ECM remodeling and are required for development. Thus, epigenetic control of endothelial gene expression programs at multiple levels is required for ECM homeostasis and embryogenesis.

**PRC2 targets numerous transcription factors that regulate developmental transitions in embryonic stem cells, and stably represses specific transcriptional programs that allow cell differentiation (Boyer et al., 2006; Lee et al., 2006) and maintenance (Delgado-Olguin et al., 2012). De-repression of key Ezh2 targets with the potential to activate gene regulatory networks destabilizes gene expression programs and could predispose to disease (Delgado-Olguin et al., 2012). Thus, identification of key Ezh2 targets could help to uncover regulators of vascular stability in human disease. Here, we uncovered Creb3l1, Klf5 and Fosl1 as Ezh2 targets able to activate a transcriptional program upstream of Mmp9 (Fig. 4G), and thus likely to contribute to vascular instability. We also identified Mmp9 as a direct target of Ezh2. The recent finding of Creb enhancing inflammation in a model of atherosclerosis (Kotla et al., 2013), coupled to the contribution of Mmp9 in atherosclerotic lesion rupture (Gough et al., 2006) and development of aortic aneurysm (Duellman et al., 2012; Longo et al., 2002), suggest that Creb-like proteins might have a function in Mmp9-related vascular disease. Indeed, both CREB3L1 and MMP9
are up-regulated in intracranial aneurysm (Li et al., 2009), which causes hemorrhage (Weir, 2002) and is associated with MMP-mediated destabilization of the arterial wall (Ishibashi et al., 2012). Future studies will be required to establish a causative function for Creb311 in vascular integrity disorders.

Ezh2 is a known positive regulator of tumor angiogenesis. For example, Ezh2 in endothelial cells promotes vessel growth in several tumor models (Dreger et al., 2012; Lu et al., 2007, 2010; Smits et al., 2011, 2010). However, our results and those of others (Mochizuki-Kashio et al., 2011) indicate that Ezh2 does not have a central function in controlling angiogenesis during embryonic development. Instead, we found that Ezh2 maintains integrity of the developing vasculature. It is likely that gene regulatory networks controlled by Ezh2 in tumor endothelial cells differ from those in embryonic endothelial cells during the formation of blood vessels. Indeed, tumor endothelial cells have been shown to have a highly unique gene expression pattern compared with other endothelial cells (St Croix et al., 2000).

A role for Ezh2 in repressing Mmp9 could have implications in the development of therapeutic strategies for cancer. MMP9 is dramatically upregulated in cancer and various inflammatory conditions, and has been proposed as a potential therapeutic target (St-Pierre et al., 2004). Therefore, identifying key regulators of MMP9 expression could provide opportunities for novel therapies. Ezh2 overexpression in various cancers correlates with tumor aggression and can serve as a prognosis indicator (Chang and Hung, 2012). Inactivation of Ezh2 inhibits metastasis, tumor angiogenesis and growth (Chang et al., 2006), and small molecule-mediated inhibition of the enzymatic function of Ezh2 may allow pharmacological treatment of cancer (Crea et al., 2012). However, as vascular instability facilitates metastasis (Nguyen et al., 2009), it is possible that Ezh2 inhibition could promote metastasis in some types of cancer. In addition, the function of Ezh2 in cardiac maintenance (Delgado-Olguin et al., 2012) raises issues regarding the potential secondary effects of inhibiting Ezh2. Therefore, experimental therapies targeting Ezh2 should address potential secondary effects on cardiovascular maintenance.

MATERIALS AND METHODS

Mice

The following mouse strains were used: Ezh2fl/fl (Su et al., 2003), Tie2::cre (Proctor et al., 2005), Rosa26TmG (Muzumdar et al., 2007) and Mmp9−/− (Cousens et al., 2000). All animal experiments followed guidelines of the University of California, San Francisco Institutional Animal Care and Use Committee, and were approved by the Toronto Centre for Phenogenomics Animal Care Committee. Ezh2fl/fl and Tie2::cre lines were backcrossed with Mmp9−/− mutants to mix the genetic backgrounds. Embryos were dissected in PBS and fixed in 4% PFA for 2 h at 4°C, dehydrated in an ethanol series and stored at −20°C until processing. Embryos were rehydrated by reversing the ethanol series and then processed for histological analysis by Haematoxylin and Eosin staining.

RNA-seq

RNA was isolated from GFP-positive cells sorted from control E10.5 Tie2::cre;Rosa26TmG and mutant Ezh2fl/fl;Tie2::cre;Rosa26TmG embryos. Cells sorted from individual embryos were used to prepare RNA-seq libraries. RNA-seq libraries were prepared using the Ovation RNA-seq System (NuGen) as recommended by the manufacturer. Differential expression was ranked by calculating the ‘differat’ or absolute difference times the ratio: abs((a−b))/(a+b) and multiple-testing-adjusted P value of P ≤ 0.01 (Thomas et al., 2011).

ChIP-seq

ChIP was performed as previously described (O’Geen et al., 2011). Three million GFP-positive cells sorted from E10.5 Tie2::cre;Rosa26TmG...
embryos were used. For data analysis, tag density was calculated within 2 kb of each transcription start site and the values were converted to log scale. For cross-referencing of RNA-seq and ChIP-seq datasets, FPKM values for each RNAseq dataset were calculated for each gene and then log normalized to a 0 to 10 point scale, with 10 representing the smallest value that captured 95% of the data. For each transcription start site, the number of H3K27me3 ChIP-seq tags within 2 kb of the transcription start site was counted and log normalized to a similar 10-point scale. Transcripts with values of 2/10 or less were categorized as having 'low' H3K27me3 signal, and genes with greater than 2/10 were categorized as having 'high' H3K27me3 signal at the TSS.

Plasmids
Expression vectors for Creb3l1, Klf5, Fosl and Cebpe were from Open Biosystems. Promoter fragments were PCR amplified using KOD DNA Polymerase (Millipore) and cloned into the XhoI site of pGL3-Basic (Promega). Mutations in putative binding sites for Creb and Klf5 of the human and mouse Mmp9 and Mmp9 promoter fragments were introduced using the Q5 Site-Directed Mutagenesis Kit (New England Biolabs). Primers are in supplementary material Table S4.

Gene expression analysis
RNA was isolated from GFP-positive cells sorted from control Ezh2floflo; Tie2::cre; RosamT/mG and mutant Ezh2floflo; Tie2::cre; RosamT/mG embryos, or from whole control embryos, using Trizol LS Reagent (Invitrogen) and treated with DNaseI. Isolation of RNA from cultured bovine aortic endothelial cells (BAECs) was performed similarly. cDNA was synthesized using SuperScript III First Strand Synthesis Kit (Invitrogen) and used for quantitative real-time PCR amplification using TaqMan probes or SYBR Green chemistry. The following TaqMan probes cDNA (10 pg) were used for quantitative real-time PCR amplification using synthesized using SuperScript III First Strand Synthesis Kit (Invitrogen). Primers are in supplementary material Table S4.

Transmission electron microscopy
Embryos were fixed in 0.1 M sodium cacodylate buffer (pH 7.4) with 2% glutaraldehyde and 1% paraformaldehyde, and post-fixed in the same buffer with 2% osmium tetroxide, then stained with 2% aqueous uranyl acetate, dehydrated in acetone, infiltrated and embedded in LX-112 resin (Ladd Research Industries). Samples were ultrathin sectioned on a Reichert Ultracut S ultramicrotome and counter stained with 0.8% lead citrate. Grids were examined on a JEOL JEM-1230 transmission electron microscope (JEOL USA) and photographed with the Gatan Ultrascan 1000 digital camera (Gatan).

Immunofluorescence
Sections (4 μm) on glass slides were fixed with 4% PFA for 10 min, washed three time for 5 min each, blocked with 5% goat serum in PBS and incubated with primary antibodies in PBS with goat serum overnight at 4°C. After three washes with PBS, sections were incubated with secondary antibodies (Alexafluor) for 2 h at room temperature, washed and mounted with ProLong Gold Antifade Reagent (Life Technologies). Antibodies and dilutions used were: Mmp9 (C20, Santa Cruz Biotechnology, 1/100), Creb3l1 (Abcam, ab33051, 1/100), Klf5 (Abgent, ABAGAP7342B, 1/100), Fosl1 (F1a1 C12, Santa Cruz Biotechnology, 1/100), phospho histone H3 (Abcam, AB5176, 1/200), activated caspase 3 (Sigma, C8487, 1/200), smooth muscle actin (Clone 1A4, A2547, Sigma, 1/200), and CD34 (Abcam, ab8158, 1/200).

In situ hybridization
Probes were synthetized from PCR fragments of mouse Mmp9, Fosl1, Klf5 and Creb3l1 cDNAs using primers containing promoters for T7 and Sp6 polymerases in the antisense and sense orientation, respectively. PCR fragments were obtained using cDNA clones from Open Biosystems as template. Antisense probes were obtained using T7 polymerase. Primers are listed in supplementary material Table S3. Probe hybridization was performed as described previously (Delgado-Olguin et al., 2012).

Luciferase
Luciferase experiments were performed in bovine aortic endothelial cells (BAEC) as previously described (Wythe et al., 2013).

Chromatin immunoprecipitation
Creb3l1- and Pol II-associated chromatin was obtained as previously described (Wythe et al., 2013) using antibodies from Abcam (Creb3l1 AB33051) and Sigma (Pol II R1530). qPCR was used to calculate the relative enrichment of Creb3l1 and RNA Pol II at the Mmp9 promoter compared with IgG control (Sigma M8695).

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Competing interests
The authors declare no competing financial interests.

Author contributions
P.D.-O. designed experiments with B.G.B. and analyzed data. P.D.-O. performed experiments. L.T.D. performed experiments in BAECs. D.H. performed ChIP on sorted cells. S.T. analyzed RNA-seq and ChIP-seq data. L.C. performed immunofluorescence, gelatinase assays and in situ hybridization. T.S. performed immunofluorescence. N.K. performed luciferase experiments. M.-W.D. generated the Ezh2flxlox line in Alexander Tarakhovsky’s lab. J.E.F. designed experiments, analyzed data, performed experiments in BAECs and edited the manuscript. B.G.B. dissected samples and analyzed data. P.D.-O. and B.G.B. wrote the manuscript with input from the authors.

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