Infantile hemangiomas (IHs) are non-malignant, large, typically cutaneous vascular tumors affecting approximately 5-10% of children to varying degrees. During the first year of life, these tumors are strongly proliferative, reaching an average size ranging from 2 to 20 cm. These lesions subsequently stabilize, undergo a spontaneous slow involution and are fully regressed by 5 to 10 years of age. Systemic treatment of infants with the non-selective β-adrenergic receptor blocker, propranolol, has demonstrated remarkable efficacy in reducing the size and appearance of IHs. However, the mechanism by which this occurs is largely unknown. In this study, we sought to understand the molecular mechanisms underlying the effectiveness of β blocker treatment in IHs. Our data reveal that propranolol treatment of IH endothelial cells, as well as a panel of normal primary endothelial cells, blocks endothelial cell proliferation, migration, and formation of the actin cytoskeleton coincident with alterations in vascular endothelial growth factor receptor-2 (VEGFR-2), p38 and cofilin signaling. Moreover, propranolol induces major alterations in the protein levels of key cyclins and cyclin-dependent kinase inhibitors, and modulates global gene expression patterns with a particular affect on genes involved in lipid/sterol metabolism, cell cycle regulation, angiogenesis and ubiquitination. Interestingly, the effects of propranolol were endothelial cell-type independent, affecting the properties of IH endothelial cells at similar levels to that observed in neonatal dermal microvascular and coronary artery endothelial cells. This data suggests that while propranolol markedly inhibits hemangioma and normal endothelial cell function, its lack of endothelial cell specificity hints that the efficacy of this drug in the treatment of IHs may be more complex than simply blockage of endothelial function as previously believed.

Introduction

Infantile hemangiomas (IHs) are the most common benign tumors in infancy affecting 5-10% of the population, and are largely composed of densely packed over-proliferating capillaries with high cellular density and the absence of an open lumen. These lesions are most prevalent in Caucasian children and are three times more common in female infants than male. The head and neck region is the most frequently involved area (60%), followed by the trunk (25%) and the extremities (15%), and these tumors exhibit a non-random distribution largely correlating with regions of embryological fusion (1). IHs have a predictable natural history, arising soon after birth to undergo a significant proliferative phase during the first year of life, followed by gradual involution over several years. Regression is complete in 50% of 5-year-old patients and 90% of 9-year-old patients. Because these tumors spontaneously regress and (for the majority of lesions) produce no long-term scarring, most children with IHs require no treatment. Despite their self-limiting course, in approximately 10% of cases depending on their anatomical site and/or size, there can be serious or life-threatening complications requiring immediate intervention. The classical approaches for treating complicated IHs include the use of systemic or intralesional corticosteroids, chemotherapeutic agents such as vincristine, laser therapy, surgical resection or a combination of these treatments. The recent serendipitous discovery of β blockers as an effective therapy for IHs has revolutionized management of IHs to become the current gold standard (2).
Cell lines and culture conditions. HemECs were previously isolated from proliferating-phase IH specimens collected from female infants (12). Primary cultures of neonatal human dermal microvascular endothelial cells (HDMVECs) and human coronary artery endothelial cells (HCAECs) were purchased from ATCC. These cell lines were cultured in vascular cell basal media (ATCC #PCS-100-030) and supplemented with 0.2% bovine brain extract, 5 ng/ml human epidermal growth factor, 10 mM L-glutamine, 0.75 U/ml heparin sulfate, 1 µg/ml hydrocortisone, 50 µg/ml ascorbic acid, 2% fetal bovine serum and penicillin/streptomycin. For all experiments cell lines were used at <10 passages.

RT-PCR. RNA was isolated from cells using the Ambion Purelink Mini kit according to the manufacturer’s directions. qRT-PCR was performed on an ABI7900HT RT-PCR system using TaqMan assays with predesigned primer sets for the genes of interest (Invitrogen). All RT-PCR experiments were performed in triplicate. Data shown are the average RQ value ± standard deviation of 4 replicates.

Western blot analysis. Cell lysates were collected after 48 h treatment and subjected to SDS-PAGE on gradient (4-15%) gels and subsequently transferred to PVDF for western blotting. p-vascular endothelial growth factor receptor-2 (VEGFR-2) (Cell Signaling #2478), VEGFR-2 (Cell Signaling #2479), p-p38 (Cell Signaling #4511), p-p44/42 (Cell Signaling #4370), p-SAPK/JNK (Cell Signaling #4668), p-ERK2 (Cell Signaling #5112), actin (Santa Cruz #SC47778), cyclin A1 (Abcam #ab13337), cyclin A2 (Abcam #7956), cyclin B2 (Abcam #18250), cyclin D1 (Cell Signaling #2978), cyclin D2 (Cell Signaling #3741), cyclin D3 (Cell Signaling #2936), cyclin E1 (Cell Signaling #4129), p5 (Cell Signaling #4822), p21 (Cell Signaling #2947), p27 (Cell Signaling #3698), cleaved caspase-9 (Cell Signaling #9509), cleaved caspase-3 (Cell Signaling #9664), p-FAK (Cell Signaling #3283), p-cofilin (Cell Signaling #3313), cofilin (Cell Signaling #3318), p-ERM (Cell Signaling #3149), ERM (Cell Signaling #3142), p-MYPT1 (Cell Signaling #4563) and MYPT1 (Cell Signaling #2634) antibodies were used at 1:1000 dilution, followed by incubation with 1:1000 HRP-conjugated anti-mouse or anti-rabbit antibodies (as appropriate). Proteins were detected using Supersignal West Dura Extended Duration Substrate (Thermo Scientific) and digitally captured using a GE Image Quant LAS4000 imaging system.

Proliferation assay. Cells were plated at subconfluent density and subjected to the indicated treatments for 48 h. Images from 5 independent areas were collected at 1-h intervals using a Nikon Biostation CT time lapse imaging robot. Changes in cell density were calculated every 24 h by counting the number of cells in the selected field of vision. Data shown represent the average of 5 independent areas ± the standard deviation.

Flow cytometry. Cells were treated as indicated, trypsinized, and fixed in 70:30 ethanol:phosphate-buffered saline overnight. Cells were then stained with 200 µg/ml ethidium bromide plus 20 µg/ml RNase A and incubated overnight. DNA content was analyzed using an Accuri C6 flow cytometer. Data shown are representative of at least 3 independent experiments. Quantitative analysis of DNA content was performed using CFlow Plus software (Accuri) and is the average of triplicate data points.

Live/dead assay. Cells were treated as indicated, stained for 10 min with 5 µg/ml Hoechst and 5 µg/ml propidium iodide, and washed 3 times in PBS. A Nikon C2SI scanning laser confocal microscope was used to image the red and blue channels. Percent apoptosis (A) was calculated by the following formula: A = (number of red cells/number of blue cells) x 100. The data presented is the average of triplicates.

Migration assay. Confluent cultures were treated as indicated, scratched wounded, and the progress of ‘healing’ of the wound was monitored using a Nikon Biostation CT time lapse imaging robot. Migration speed was calculated by monitoring the movement of the ‘wound’ toward its center at each hour over a 12-h period.

Immunofluorescence and cytoskeletal organization calculations. Cells were grown on glass coverslips, treated as indicated and fixed in 4% paraformaldehyde. Then, the coverslips were blocked in 5% bovine serum albumin plus 0.5% Tween-20,
incubated with 1:200 of the p-FAK antibody and detected with fluorescently conjugated secondary antibodies. Actin microfilaments were detected by staining with Rhodamine-conjugated phalloidin, and cell nuclei were detected with 4',6-diamidino-2-phenylindole (DAPI). Immunofluorescent images were captured as z-stacks using a Nikon C2SI scanning laser confocal microscope. Image analysis of cytoskeletal organization included calculating the actin stress fiber correlation and binarizing this correlation image to determine fiber lengths using the FiberScore algorithm (13).

Microarray analysis. Total RNA was amplified and biotin-labeled using Illumina TotalPrep RNA Amplification kit (Ambion). A total amount of 750 ng of biotinylated aRNA was then briefly heat-denatured and loaded onto expression arrays to hybridize overnight. Following hybridization, arrays were labeled with Cy3-streptavidin and imaged on the Illumina ISCAN. Intensity values were transferred to Agilent GeneSpring GX microarray analysis software and data were filtered based on the quality of each call. Statistical relevance was determined using ANOVA with a Benjamini Hochberg FDR multiple testing correction (p<0.05). Data were then limited by fold change analysis to statistically relevant data points demonstrating a 2-fold or more change in expression.

Results

β-adrenergic receptor expression in HemECs and IHs. The presence of β-adrenergic receptors on normal human endothelial cells has been previously confirmed (14). However, despite the extensive use of systemic propranolol as an anti-IH agent, the expression of the three known β-adrenergic receptors in endothelial cells isolated from these benign tumors is unknown. Using RT-PCR, we evaluated the steady state mRNA expression of the three known β-adrenergic receptors (ADRB1, ADRB2 and ADRB3) in cultured HemECs. Our data revealed that ADRB1 and 2, although not ADRB3, were expressed in HemECs (Fig. 1). Moreover, similar results were observed for both HDMVECs and HCAECs, with equivalent levels of each receptor across the three endothelial cell lines.

Propranolol disrupts cell cycle progression. Despite the extensive use of propranolol, many of the mechanisms of action of this drug on IHs have been inferred from its effects on normal endothelial cells (7-9). Recent studies have suggested that propranolol may inhibit IHs by suppressing production of nitric oxide and HIF1α signaling (10,11). However, the signaling intermediates and many of the downstream effectors which modulate its action on IHs are largely unknown. To elucidate the molecular components at play following propranolol-induced inhibition of HemEC proliferation, we first examined the growth rates of HemECs, HDMVECs and HCAECs after treatment with a dose curve of propranolol. Our data indicate that the IC_{50} for propranolol-induced inhibition of proliferation was ~50 µM for all three cell types (Fig. 2A and B), therefore for all subsequent experiments in this study we continued to use this concentration. Moreover, cell cycle analysis on the panel of endothelial cells using flow cytometry revealed that propranolol indiscriminately induced an increase in the proportion of cells in the G1 phase of the cell cycle, while reducing the proportion of cells in the S and G2/M phases (Fig. 2C, Table I). Equivalent results were observed in HDMVECs and HCAECs (Table I). To address the effects of propranolol on HIHEC proliferation, we analyzed the expression/activation status of a number of proteins involved in regulating proliferation. VEGFR-2 is a strong mitogenic regulator of endothelial cells that shows aberrant constitutive activation in HemECs (15), and its phosphorylation is reportedly blocked following propranolol treatment (5). Indeed, the 24-h treatment of HemECs with 50 mM propranolol resulted in sharply decreased VEGFR-2 phosphorylation (Fig. 2D). The mitogen activated protein kinases (MAPKs) are direct downstream effectors of VEGFR-2 regulating VEGF-induced endothelial proliferation. We tested the activation status of p38, p44, p42, SAPK, JNK, and the downstream effector ATF4 in HemECs experiencing 24 h of propranolol treatment. Of the proteins tested, the stress activated p38 (but not the stress activated SAPK or JNK) was the only one that exhibited a significant change in phosphorylation following propranolol treatment of HemECs (Fig. 2D). These data suggest that despite the inhibition of VEGFR-2 noted following the treatment, the major proliferative MAPKs such as p44 and p42 were not affected by propranolol treatment in HemECs. As flow cytometry analysis indicated that propranolol induced alterations in cell cycle progression, we performed western blot analysis on a panel of cell cycle regulators, discovering that this drug decreases the expression of key cyclin proteins (cyclins A1, A2, B2, D2 and D3) and increases the expression of important cell cycle inhibitors (p15, p21 and p27) (Fig. 2E). No change in the expression of Cdk2 or Cdk4 was observed following the treatment. These alterations in key cell cycle regulators likely account for propranolol-induced alterations in HemEC proliferation.

It is speculated that propranolol may increase apoptosis of IHs. To determine whether this drug affects apoptosis, we treated HemECs, HDMVECs and HCAECs with 50 µM propranolol for 3 days. As a control we treated HemECs with 5 µM cisplatin for an equivalent amount of time. Cells were co-stained with propidium iodide (which only stains the nuclei...
of dead cells) and Hoechst dye (which stains the nuclei of both live and dead cells). Calculation of the apoptotic index from each treatment revealed that 50 µM propranolol did not induce apoptosis of any of the cell lines tested, while 5 µM cisplatin resulted in almost 100% apoptosis (Fig. 3A and B). We did observe significant apoptosis in all of our cell lines at concentrations of propranolol higher than 150 µM (data not shown). To confirm our observations, we utilized western blotting to detect the cleavage products of the apoptotic initiator caspase-9 and the apoptotic effector caspase-3. Our data indicate that while 5 µM cisplatin strongly induced caspase cleavage, 50 µM propranolol failed to induce apoptotic signaling (Fig. 3C).

**Figure 2. Propranolol decreases the proliferation of human infantile hemangioma endothelial cells (HemECs).** (A) HemECs, human dermal microvascular endothelial cells (HDMVECs), and human coronary artery endothelial cells (HCAECs) were treated with a dose curve of propranolol (0 to 100 µM) and cell proliferation was measured by counting changes in the number of cells/defined vision field over a 48-h period. (B) Time lapse microscopy image of sham and 50 µM propranolol treated HemECs over a 48-h period. (C) DNA content analysis of propidium iodide stained HemECs treated with sham or 50 µM propranolol for 48 h. (D) Western blot analysis detecting the levels of phosphorylated and total vascular endothelial growth factor receptor-2 (p-VEGFR-2 and VEGFR-2, respectively) and the phosphorylated forms of p38 (p-p38), p44 (p-p44), p42 (p-p42), stress activated protein kinase (p-SAPK), c-jun N-terminal kinase (p-JNK), and activating transcription factor 4 (p-ATF4) in HemECs treated for 24 h with sham or 50 µM propranolol. Actin levels were used as a loading control. (E) Western blot analysis detecting the levels of cyclins, cyclin dependent kinases, and cyclin dependent kinase inhibitors in HemECs treated for 24 h with sham or 50 µM propranolol. Actin levels were used as a loading control. Prop, propranolol.

**Propranolol disrupts cell migration and actin cytoskeleton dynamics.** Several reports have presented mixed results for the role of β-adrenergic receptor signaling in wound healing and cell migration, with evidence that inhibition of this class of receptors delays (16-19) or promotes (20-22) wound healing. Moreover, in cultured bovine aortic endothelial cells, β-adrenergic blockade with propranolol reportedly inhibits norepinephrine-induced induction of actin stress fibers (8), thus we sought to determine if similar effects on cell migration and cytoskeletal organization could be observed in HemECs treated with propranolol. HemECs, HDMVECs and HCAECs were grown to confluence, manually scratch wounded with a micropipette tip, and images taken using time lapse microscopy over a period of 12 h. As illustrated in Fig. 4A, treatment of HemECs with 50 µM propranolol resulted in a significant reduction in ‘wound’ closure compared to the control. Quantification of the time lapse images taken from the scratch migration assay revealed that propranolol dramatically reduced the migratory
speed of HemECs (34% reduction), HMVECs (66% reduction) and HCAECs (67% reduction) (Fig. 4B), suggesting that propranolol is more effective at blocking proliferation of normal endothelial cells than HemECs. To identify signaling events that might shed light on how propranolol disrupts migration, we performed western blot analysis to detect the activation status of several known regulators of actin cytoskeletal dynamics including focal adhesion kinase (FAK), coflin, ezrin/radixin/moesin (ERM), and myosin phospha-
tase (MYPT1), revealing that this drug effectively decreases the inhibitory phosphorylation of coflin (an actin severing protein) at serine-3 (Fig. 4C). Given the increased activation of coflin following propranolol treatment, we suspected that changes in the actin microfilament cytoskeleton would ensue. Indeed, immunofluorescent detection of actin stress fibers revealed that propranolol markedly inhibits actin polymerization in HemECs (Fig. 4D) and normal endothelial cells (data not shown) consistent with that expected from activation of coflin. Computational analysis of actin stress fiber length using the FiberScore algorithm (Lichtenstein) demonstrated that propranolol-treated HemECs exhibit a greater than 1.5-fold reduction in average fiber length compared to the sham treatment (data not shown). Similar observations were observed for non-hemangioma endothelial cells (data not shown). In addition to altering actin stress fiber polymerization, propranolol shifted the subcellular localization of p-FAK from regions of colocalization with actin stress fibers in sham-treated cells to diffuse punctuate regions located throughout the cytoplasm in propranolol-treated cells (Fig. 4D). Despite alterations in p-FAK subcellular localization, no changes in the levels of p-FAK were observed in response to propranolol (Fig. 4C).

Propranolol disrupts global gene expression patterns in endothelial cells. Propranolol has been shown to affect the expression of cyclins across multiple cell types (5, 23), gluco-

| Cells          | Sham | Propranolol |
|---------------|------|-------------|
| HemECs G1     | 68±2.3 | 74±2.2 |
| HemECs S      | 8±0.6  | 5±0.3  |
| HemECs G2/M   | 24±2.7 | 21±1.1 |
| HDMVECs G1    | 69±3.0 | 75±1.6 |
| HDMVECs S     | 8±4.1  | 4±0.0  |
| HDMVECs G2/M  | 22±5.9 | 20±4.5 |
| HCAECs G1     | 71±1.4 | 76±1.7 |
| HCAECs S      | 5±1.6  | 3±1.3  |
| HCAECs G2/M   | 23±3.3 | 20±2.5 |

HemECs, human infantile hemangioma endothelial cells; HDMVECs, human dermal microvascular endothelial cells; HCAECs, human coronary artery endothelial cells.

Figure 3. Propranolol does not induce apoptosis in human infantile hemangioma endothelial cells (HemECs) at its effective inhibitory concentration. (A) Confocal imaging of HemECs treated for 72 h with sham or 50 µM propranolol and subsequently co-stained with propidium iodide (PI) and Hoechst dye (blue, Hoechst-positive nuclei; pink, Hoechst-positive/PI-positive nuclei). (B) Quantification of PI-positive nuclei in HemECs, human dermal microvascular endothelial cells (HDMVECs), and human coronary artery endothelial cells (HCAECs) treated for 72 h with sham or 50 µM propranolol. (C) Western blot analysis detecting the levels of cleaved caspase-9 and -3 (cl-caspase-9 and cl-caspase -3, respectively). Actin levels were used as a loading control.
neogenic and glycolytic enzymes in the liver (24), epidermal growth factor 1 in cardiomyocytes (25) and pigment epithelial derived factor in the retina (26). However, these studies have focused on small subsets of genes and did not look at large-scale changes in genomic expression patterns. To evaluate the global gene expression changes in HemECs in response to propranolol and to examine how the identified changes compared with those observed in propranolol-treated normal human endothelial cells, we performed whole genome microarrays providing coverage for more than 47,000 transcripts and known splice variants across the human transcriptome. Our analysis identified 89 genes whose expression in HemECs was altered greater than 2-fold (p<0.05) in response to propranolol (32 genes significantly upregulated and 57 genes downregulated) (Table II). Several functional groupings of genes were identified included those involved in lipid and sterol metabolism (21% of total gene expression changes: HMGCS1, MSMO1, LDLR, DHCR7, SCD, ACAT2,
Table II. Alterations in gene expression (fold-change) induced by propranolol treatment.

| Gene symbol | Gene name | Accession no. | HIHEC | HDMVEC | HCAEC |
|-------------|-----------|---------------|-------|--------|-------|
| HMGCS1      | 3-Hydroxy-3-methylglutaryl-CoA synthase 1 | NM_002130.6 | 4.6   | 5.8    | 6.2   |
| MSMO1       | Methylsterol monooxygenase 1, TV2 | NM_001017369.2 | 4.5   | 4.0    | 5.8   |
| INSG1       | Insulin induced gene 1 | NM_198336.2 | 4.3   | 4.6    | 4.9   |
| LDLR        | Low density lipoprotein receptor | NM_000527.4 | 3.6   | 3.8    | 3.9   |
| MVD         | Mevalonate decarboxylase | NM_002461.1 | 3.6   | 5.7    | 3.4   |
| DHCR7       | 7-Dehydrocholesterol reductase | NM_001360.2 | 3.6   | 4.7    | 3.4   |
| SCD         | Steroyl-CoA desaturase | NM_005603.4 | 3.3   | 3.2    | 5.0   |
| ACAT2       | Acetyl-CoA acetyltransferase 2 | NM_005891.2 | 3.2   | 4.6    | 5.2   |
| LSS         | Lanosterol synthase | NM_002340.5 | 3.2   | 4.5    | 5.1   |
| TM7SF2      | Transmembrane 7 superfamily member 2 | NM_003273.2 | 3.0   | 4.8    | 5.2   |
| HMGCR       | 3-Hydroxy-3-methylglutaryl-CoA reductase | NM_000859.2 | 2.9   | 3.1    | 3.8   |
| FASN        | Fatty acid synthase | NM_004104.4 | 2.8   | 4.6    | 4.3   |
| MSMO1       | Methylsterol monooxygenase 1, TV1 | NM_006745.4 | 2.8   | 2.0    | 3.0   |
| SQuEL       | Squalene epoxidase | NM_003129.3 | 2.7   | 2.6    | 3.6   |
| PGS4        | Pregnancy specific β-1-glycoprotein 4 | NM_002780.3 | 2.6   | 1.3    | 4.5   |
| DHCR24      | 24-Dehydrocholesterol reductase | NM_014762.3 | 2.5   | 2.4    | 3.3   |
| FDFT1       | Farnesyl-diphosphate farnesyltransferase 1 | NM_004462.3 | 2.5   | 2.2    | 3.2   |
| IDI1        | Isopentenyl-diphosphate δ isomerase 1 | NM_004508.2 | 2.4   | 2.3    | 3.4   |
| FADS2       | Fatty acid desaturase 2 | NM_004265.2 | 2.4   | 4.2    | 2.8   |
| NPC1        | Niemann-Pick disease, type C1 | NM_002071.4 | 2.3   | 2.3    | 3.8   |
| PFKFB4      | Fructose-2,6-bisphosphatase 4 | NM_004567.2 | 2.2   | 2.8    | 2.3   |
| ACS5        | Acyl-CoA synthetase family member 2, TV2 | NM_001707655.2 | 2.2   | 2.6    | 3.5   |
| ACS7        | Acyl-CoA synthetase family member 2, TV2 | NM_018677.3 | 2.2   | 2.7    | 3.2   |
| EBP         | Emopamil binding protein | NM_006579.2 | 2.1   | 2.4    | 2.3   |
| LOC100129668| LOC100129669 | XM_001713607.1 | 2.1   | 2.2    | 2.5   |
| HMOX1       | Heme oxygenase (decycling) 1 | NM_002133.2 | 2.1   | 2.1    | 3.5   |
| SCD5L       | Sterol-C5-desaturase-like | NM_006918.4 | 2.1   | 1.4    | 2.4   |
| NSDHL       | NAD(P) dependent steroid dehydrogenase-like | NM_015922.2 | 2.1   | 2.3    | 2.2   |
| P2RX4       | Purinergic receptor P2X, 4 | NM_002560.2 | 2.1   | 1.7    | 1.8   |
| LPIN1       | Lipin 1 | NM_145693.1 | 2.0   | 1.6    | 2.9   |
| PGF         | Placental growth factor | NM_002632.5 | 2.0   | 1.7    | 2.3   |
| ANGPT2      | Angiopoietin | NM_001147.2 | 2.0   | 1.0    | 2.1   |
| LOC729009   | LOC729010 | XR_024330.1 | 2.0   | 1.6    | 2.6   |
| IL8         | Interleukin 8 | NM_000584.3 | -2.0  | -2.9   | -3.1  |
| CDK1        | Cyclin-dependence kinase 1 | NM_001786.4 | -2.0  | -1.8   | -2.1  |
| TUBB2C      | Tubulin, β 4B 1v | NM_006088.5 | -2.0  | -1.4   | -2.5  |
| PTGT1       | Pituitary tumor-transforming 1 | NM_004219.2 | -2.0  | -2.0   | -2.0  |
| OIP5        | Opa interacting protein 5 | NM_007280.1 | -2.0  | -2.3   | -2.1  |
| CDA8        | Cell division cycle associated 8 | NM_018101.3 | 2.0   | -1.4   | -2.3  |
| TAGLN       | Transgelin | NM_003186.3 | -2.0  | -1.7   | -2.9  |
| CDKN3       | Cyclin-dependent kinase inhibitor 3 | NM_005192.3 | -2.0  | -1.7   | -1.6  |
| ANLN        | Anillin, actin binding protein | NM_018685.2 | -2.0  | -1.8   | -1.7  |
| HJURP       | Holliday junction recognition protein | NM_018401.3 | -2.0  | -1.2   | -2.0  |
| PBK         | PDZ binding kinase | NM_018492.2 | -2.0  | -1.6   | -2.5  |
| UBE2T       | Ubiquitin-conjugating enzyme E2T (putative) | NM_014176.3 | -2.0  | -1.4   | -1.5  |
| STEAP1      | 6-Transmembrane epithelial antigen of the prostate 1 | NM_012449.2 | -2.0  | -1.8   | -1.8  |
| UBE2C       | Ubiquitin-conjugating enzyme E2C, TV3 | NM_181800.1 | -2.0  | -1.9   | -2.8  |
| CKS1B       | CDC28 protein kinase regulatory subunit 1B | NM_001826.2 | -2.0  | -1.6   | -1.9  |
| TACC3       | Transforming, acidic coiled-coil containing protein 3 | NM_006342.2 | -2.0  | -1.4   | -1.8  |
| NCPG        | Non-SMC condensin I complex, subunit G | NM_002133.2 | -2.0  | -1.7   | -1.6  |
| PCDH7       | Protocadherin 7 | NM_002589.2 | -2.0  | -1.2   | -2.2  |
| FAM64A      | Family with sequence similarity 64, member A | NM_019013.3 | -2.1  | -1.2   | -2.0  |
| PRC1        | Protein regulator of cytokinesis 1 | NM_199413.1 | -2.1  | -1.5   | -2.3  |
| MELK        | Maternal embryonic leucine zipper kinase | NM_014791.3 | -2.1  | -1.8   | -2.1  |
| TPX2        | TPX2, microtubule-associated | NM_012112.4 | -2.1  | -1.4   | -2.2  |
| MCM4        | Minichromosome maintenance complex CMPT 4, TV2 | NM_182746.2 | -2.1  | -1.6   | -1.9  |
Table II. Continued.

| Gene symbol | Gene name                        | Accession no. | HIHEC | HDMVEC | HCAEC |
|-------------|----------------------------------|---------------|-------|--------|-------|
| ZWINT       | ZW10 interactor                  | NM_001005413.1 | -2.1  | -1.5   | -2.0  |
| KIFC1       | Kinesin family member C1         | NM_002263.2   | -2.1  | -1.4   | -2.2  |
| CDC20       | Cell division cycle 20           | NM_001255.2   | -2.2  | -2.0   | -4.0  |
| UBE2C       | Ubiquitin-conjugating enzyme E2C, TV6 | NM_181803.1 | -2.2  | -1.8   | -2.4  |
| NCAPG2      | Non-SMC condensin II complex, subunit G2 | NM_017760.5 | -2.2  | -1.3   | -1.4  |
| SERPIN1D1   | Serpin peptidase inhibitor, clade D, member 1 | NM_000185.3 | -2.2  | -1.8   | -2.6  |
| CDC45L      | Cell division cycle 45           | NM_003504.3   | -2.2  | -1.8   | -3.0  |
| LYAR        | Ly1 antibody reactive            | NM_017816.2   | -2.2  | -1.6   | -1.3  |
| CCNA1       | Cyclin A1                       | NM_003914.3   | -2.2  | -2.2   | -1.9  |
| TRIP1       | Thyroid hormone receptor interactor 13 | NM_004237.3 | -2.2  | -1.9   | -2.6  |
| MPZL2       | Myelin protein zero-like 2, TV2  | NM_144765.2   | -2.2  | -1.3   | -2.4  |
| CEP55       | Centrosomal protein 55kDa       | NM_018131.4   | -2.2  | -2.0   | -2.1  |
| CXCL1       | Chemokine (C-X-C motif) ligand 1 | NM_001511.3   | -2.2  | -2.5   | -2.8  |
| CCNB2       | Cyclin B2                       | NM_004701.3   | -2.2  | -2.2   | -2.3  |
| KIF20A      | Kinesin family member 20A       | NM_005733.2   | -2.2  | -1.9   | -2.5  |
| RAD51AP1    | RAD51 associated protein 1       | NM_006479.4   | -2.2  | -1.6   | -2.2  |
| GINS2       | GINS complex subunit 2          | NM_016095.2   | -2.2  | -1.7   | -2.9  |
| FM83D       | Family with sequence similarity 83, member D | NM_030919.2 | -2.3  | -1.6   | -2.4  |
| KIAA0101    | KIAA0101                        | NM_014736.4   | -2.3  | -2.0   | -2.3  |
| DLGAP5      | Discs, large (Drosophila) homolog-associated protein 5 | NM_014750.4 | -2.3  | -2.0   | -2.3  |
| CCNA2       | Cyclin A2                       | NM_012137.3   | -2.3  | -2.2   | -2.8  |
| LOC399942   | LOC399943                       | XM_934471.1   | -2.3  | -2.4   | -3.4  |
| MPZL2       | Myelin protein zero-like 2, TV1  | NM_005797.3   | -2.3  | -2.7   | -2.2  |
| TOP2A       | Topoisomerase II α 170kDa       | NM_001067.3   | -2.3  | -2.4   | -2.6  |
| RRM2        | Ribonucleotide reductase M2      | NM_001034.3   | -2.3  | -1.5   | -2.8  |
| FBXO5       | F-box protein 5                  | NM_012177.3   | -2.4  | -1.9   | -2.6  |
| CDC45       | Cell division cycle associated 7 | NM_031942.4   | -2.4  | -1.9   | -2.5  |
| MCM4        | Minichromosome maintenance complex CMPT 4, TV1 | NM_005914.3 | -2.4  | -1.5   | -2.0  |
| MAD2L1      | MAD2 mitotic arrest deficient-like 1 | NM_002358.3 | -2.4  | -2.3   | -2.1  |
| UHRF1       | Ubiquitin-like with PHD and ring finger domains 1 | NM_001048201.1 | -2.5 | -1.6   | -2.6  |
| ANGPTL4     | Angiopoietin-like 4              | NM_139314.1   | -2.8  | -2.8   | -2.9  |
| RGS4        | Regulator of G-protein signaling 4 | NM_005613.5 | -3.0  | -3.8   | -3.8  |
| IL1RL1      | Interleukin 1 receptor-like 1    | NM_003856.2   | -3.2  | 3.4    | -5.2  |

HDMVEC, human dermal microvascular endothelial cells; HCAEC, human coronary artery endothelial cells.

Discussion

IHs as a whole are largely understudied considering the high prevalence of these lesions in children and the serious threat to health they pose in certain instances. To date, there remains a great deal of uncertainty as to the origin of these tumors, with evidence suggesting they may be caused by aberrant transplantation of placental endothelial cells (27), predisposing genetic factors (28,29) and/or tumor stem cell components (30). Despite the controversial origin of these tumors, proliferating IHs are characterized by an enhanced angiogenic capacity largely due to modulation of signaling pathways that regulate the VEGF signaling axis, while involuting IHs display a chronic inflammatory response and downregulation of angiogenesis regulators (31). The recent discovery that the β blocker propranolol is an effective treatment for IHs suggests that the sympathetic nervous system may play a key role in controlling IH growth. Epinephrine is a sympathomimetic amine...
As pericytes are responsible for angiogenesis (50) and recent reports suggest that it may work in part through mechanisms similar to that noted in normal endothelial cells, presumably believed to induce IH tumor regression through mechanisms of propranolol in IH tumors. This drug is approved for IHs, very little has been done to determine the molecular mechanisms underlying this effect remain to be determined.

Figure 5. Propranolol induces significant alterations in global gene expression of human infantile hemangioma endothelial cells (HemECs). (A) Correlation map comparing the significant gene expression changes (>2 fold gene expression alteration, p<0.05) as determined by microarray analysis between HemECs, human dermal microvascular endothelial cells (HDMVECs), and human coronary artery endothelial cells (HCAECs) treated with sham or 50 µM propranolol for 24 h. (B) RT-PCR confirmation of a subset of genes in HemECs whose expression was statistically altered in the microarray.

that increases the activity of noradrenaline in post-synaptic cells, and is capable of enhancing vasodilation through activation of β-adrenergic receptors. β-adrenergic receptors have been shown to be expressed on normal capillary endothelial cells (32) and it is believed that β blockers, such as propranolol, inhibit epinephrine signaling through inducing vasoconstriction of endothelial cells and disruptions in key angiogenic processes (7-9,33). Moreover, β blockers have been shown to reduce the expression of VEGF in non-endothelial cells, thus leading to inhibition of angiogenic paracrine signaling (34). Despite the extensive use of propranolol in the treatment of IHs, very little has been done to determine the molecular mechanisms of propranolol in IH tumors. This drug is presumably believed to induce IH tumor regression through mechanisms similar to that noted in normal endothelial cells, and recent reports suggest that it may work in part through suppressing production of nitric oxide and HIF1α regulation of VEGF expression (10,11). In this study, we sought to investigate how propranolol disrupts HHIEC function and compare these effects to those seen in normal primary endothelial cell lines. Our data demonstrated that β-adrenergic receptors are expressed across a panel of HHIEC and normal endothelial cells. We further showed that propranolol disrupts HHIEC and normal endothelial cell cycle progression, migration, cytoskeletal dynamics, and gene expression, and we elucidated multiple downstream targets of propranolol including cell cycle progression regulators, cytoskeletal modulators and gene expression alterations.

The expression of β1- and β2-adrenergic receptors has been extensively studied in the cardiovascular system, with high expression occurring in cardiac myocytes and vascular smooth muscle cells (35). Although β3-knockout mice display increased hypotension in response to isoproterenol (36), these receptors are suspected to play a lesser role in cardiovascular function compared to β1- and β2- receptors as they are expressed primarily in brown adipocytes, gallbladder and the colon (37). Our data indicate that both β1- and β2- (but not β3-) adrenergic receptors are expressed on primary cultures of HemECs. Interestingly, comparisons of the relative mRNA expression levels of these receptors on primary cultures of non-diseased endothelial cells revealed similar levels to that of HemECs, causing us to question if propranolol is selective for HemECs or if this drug demonstrates a similar level of inhibition for diseased and normal endothelial cells. Indeed, comparisons of the inhibitory effect of propranolol at its IC50 on cultures of HemECs, HDMVECs, and HCAECs revealed that this drug indiscriminately blocks proliferation, migration, and actin polymerization in an endothelial cell-type independent manner. This finding suggests that the mechanism of action for propranolol on IHs may extend beyond simply blocking endothelial cell function. For instance, IHs display high pericyte density in the proliferating stage (38) and increased hypotension in response to isoproterenol (36), these effects to those seen in normal primary endothelial cell lines. Further studies should examine whether propranolol inhibits IH growth through destabilization of endothelial cell/pericyte interactions. Another possibility that may account for the endothelial cell-type independent action of propranolol may have to do with the limitations of in vitro monolayer cell culture systems. Children undergoing systemic propranolol treatment for IHs often undergo side effects including bradycardia, hypotension and hypoglycemia (40), however significant disruptions of their existing vascular beds are not reported. This suggests that propranolol may preferentially inhibit proliferating endothelial vasculature while sparing the quiescent established vasculature. However, this possibility is complicated by reports suggesting that propranolol improves wound healing - a process intimately dependent on neovascularization (20-22).

There is evidence that VEGFR-2 phosphorylation is controlled by β-adrenergic signaling (5,41,42), however the mechanisms underlying this effect remain to be determined. As HemECs are characterized by aberrant constitutive activa-
tion of VEGFR-2 signaling, we sought to determine whether propranolol is capable of attenuating this process. Similar to data reported in normal endothelial lines, propranolol effectively blocks VEGFR-2 phosphorylation on HemECs. We tested the effects of propranolol on known downstream targets of VEGF signaling revealing propranolol-induced alterations in p38 signaling, decreased cyclin expression and increased cyclin-dependent kinase inhibitor steady state mRNA levels. Moreover, propranolol treatment of the panel of endothelial cells resulted in reduced proliferation rates and increased percentages of cells in the G1 cell cycle phase. These alterations were coincident with significant changes in the levels of key cyclins and cell cycle inhibitors. Interestingly, of the panel of MAPK proteins that we tested, we saw increased phosphorylation only in p38, which is known to be responsive to stress stimuli such as cytokines, irradiation and shock. p38 plays a central role in inflammation and regulates the production of inflammatory mediators such as TNFα, IL1β, and COX2 (43), thus it is possible that increased p38 activation in propranolol-treated IHs may mediate IH regression through immune-mediated responses. A number of studies suggest that propranolol may induce apoptosis of HemECs. No caspase cleavage or apoptosis was observed at the IC50 (~50 µM) for propranolol in HemECs or normal endothelial cells, although we did begin to see lethal effects of this treatment in all three endothelial cell lines at upwards of 150 µM. These findings do not rule out that propranolol-induced IH apoptosis plays a role in the efficacy of this treatment, but it does suggest that basic endothelial functions such as proliferation and migration display greater susceptibility to lower doses of propranolol than does apoptosis. We demonstrated that propranolol treatment of HemECs results in abolished stress fiber formation, and this effect may be due in part to decreased levels of phosphorylated cofilin following propranolol treatment. Cofilin is a cytoskeletal-binding protein critical for actin microfilament dynamics and reorganization by severing and depolymerizing actin filaments (44). Cofilin phosphorylation is an inhibitory event (45), thus the absence of stress fiber formation observed in propranolol-treated HemECs may be due in part to increased cofilin-mediated actin severing. This effect would certainly disrupt cell migration, and as the actin cytoskeleton is intimately tied to the regulation of cell cycle progression (46), may indirectly contribute to propranolol induced decreased cell proliferation.

As propranolol appears to work with great efficacy against IHs, similar inhibitory effects could potentially be observed in other vascular tumors such as angiosarcomas and Kaposi’s sarcomas. Indeed, propranolol has been tested in preclinical and clinical models of malignant tumors, demonstrating good efficacy in the treatment of melanoma (47), pancreatic (48), colorectal (49) and breast (50) cancer. Finally, given the cutaneous nature of IHs and the endothelial cell type-independent effects of propranolol observed in our study, topical delivery of β blockers (as opposed to systemic delivery) should be aggressively pursued. A controlled study of topical administration of the β blocker timolol on non-life threatening IHs revealed consistently good to moderate responses in 91.5% of infants (51), suggesting this therapy could specifically treat the lesion area while preventing potential collateral anti-vascular effects on the normal endothelium.

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