

Endothelins are vascular-derived axonal guidance cues for developing sympathetic neurons

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During development, sympathetic neurons extend axons along a myriad of distinct trajectories, often consisting of arteries, to innervate one of a large variety of distinct final target tissues. Whether or not subsets of neurons within complex sympathetic ganglia are predetermined to innervate select end-organs is unknown. Here we demonstrate in mouse embryos that the endothelin family member Edn3 (ref. 1), acting through the endothelin receptor EdnrA (refs 2, 3), directs extension of axons of a subset of sympathetic neurons from the superior cervical ganglion to a preferred intermediate target, the external carotid artery, which serves as the gateway to select targets, including the salivary glands. These findings establish a previously unknown mechanism of axonal pathfinding involving vascular-derived endothelins, and have broad implications for endothelins as general mediators of axonal growth and guidance in the developing nervous system. Moreover, they suggest a model in which newborn sympathetic neurons distinguish and choose between distinct vascular trajectories to innervate their appropriate end organs.

The sympathetic division of the autonomic nervous system is composed of preganglionic sympathetic neurons, derived from the neuroectoderm, and their synaptic targets, neural-crest-derived postganglionic sympathetic neurons, the cell bodies of which reside within paravertebral and prevertebral sympathetic ganglia. Postganglionic sympathetic neurons (referred to hereafter as sympathetic neurons) innervate and control a wide range of targets, including exocrine and endocrine glands and ducts, smooth muscle layers of the intestine and blood vessels, cardiac muscle and nodes, and pilomotor muscles. Sympathetic neurons originate during development when neural crest cells bilaterally delaminate from the neural tube, migrate and assemble into ganglia. In mouse embryos, aggregation of neural crest cells into sympathetic chain ganglia initiates at approximately embryonic day 10.5 (~E10.5), adjacent to the dorsal aorta. The cranial-most sympathetic ganglia, the superior cervical ganglia (SCG), ultimately come to reside adjacent to the bifurcation of the internal and external carotid arteries from the common carotid arteries. Sympathetic neurons of the SCG send axonal projections either along the external carotid arteries to innervate the submandibular, sublingual and parotid glands or along the internal carotid arteries to the lacrimal and pineal glands, the eye, blood vessels and skin of the head, and the mucosa of the oral and nasal cavities.

A fundamental, unanswered question is how subsets of neurons within any complex autonomic ganglion, such as the SCG, acquire characteristic molecular and functional properties appropriate for the control of their respective end organs. One model posits that axons emanating from the SCG or other ganglia grow along

intermediate targets, such as blood vessels, in a random or stochastic manner, and that it is the end organ that retrogradely specifies morphological and biochemical features, presynaptic connections and physiologic properties of the innervating neuron. Evidence in support of this model derives from the observation that a small subset of sympathetic neurons acquires a cholinergic transmitter phenotype on innervation of eccrine sweat glands and acquisition of a sweat-gland-derived cholinergic differentiation factor (CDF)⁴. A second model posits that subpopulations of newly born sympathetic neurons are molecularly distinct; these subpopulations choose from several intermediate target structures, such as particular blood vessels that serve to guide axonal trajectories to their appropriate end organs. Identification of axonal guidance cues that direct select subsets of sympathetic axons towards one or another vascular path would serve as evidence in support of the latter model. We therefore asked whether axons of developing sympathetic neurons of the SCG choose between extending along either the internal or the external carotid arteries because these blood vessels provide the main routes by which SCG axons project to distinct end-organs in the head and neck. These investigations led us to define the molecular identity of the cues and their receptors that guide extending axons along the vascular network.

In mouse embryos, the SCG form in the upper thorax by E11.5 as a condensation of neural precursors dorsal to the outflow tract of the heart. SCG neurons extend axons cranially along the primitive internal carotid arteries (derived from the dorsal aortae; Fig. 1a, d). At this stage, the external carotid arteries are beginning to emerge from the third pharyngeal arch arteries near their origins from the aortic sac⁵; there are no projections of sympathetic axons along either the nascent external carotid arteries or the third arch arteries (Fig. 1a, g). By E12.5, the common carotid arteries have elongated and the external carotid arteries are substantially developed. At this time, the sympathetic chain has become delimited into distinct ganglia and the SCG are clearly distinct from the more caudal stellate ganglia. Sympathetic neurons initiate extension of axons towards the external carotid arteries at this time, originating from the SCG at the level of the junction of the base of internal and external carotid arteries (Fig. 1b, m, p); the SCG extends cranially along the internal carotid arteries as far as the stapediaal arteries (Fig. 1b, j). By E13.5, SCG axonal projections associated with both the external and internal carotid arteries are more substantially developed, although the general pattern of blood vessels and axonal projections is the same as the previous day (Fig. 1c, q, t, w and Supplementary Figs 1 and 2).

Previous studies using Wnt1Cre and R26R mice have defined the neural crest and mesodermal origins of vascular smooth muscle in the cardiac outflow tract and great blood vessels, although not specifically of the vascular segments relevant for SCG projections^{6,7}. The

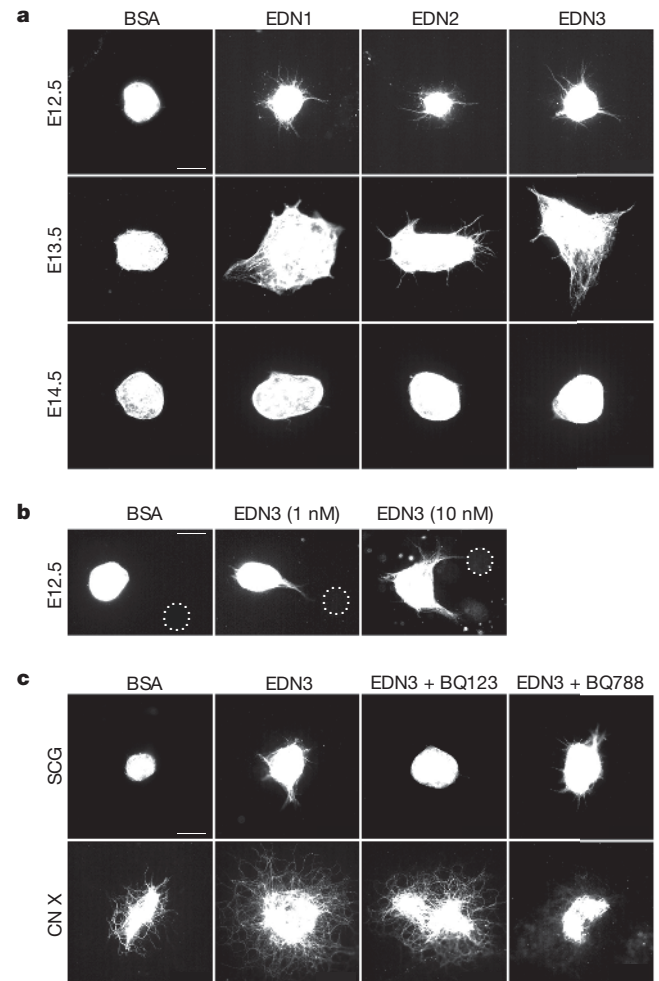
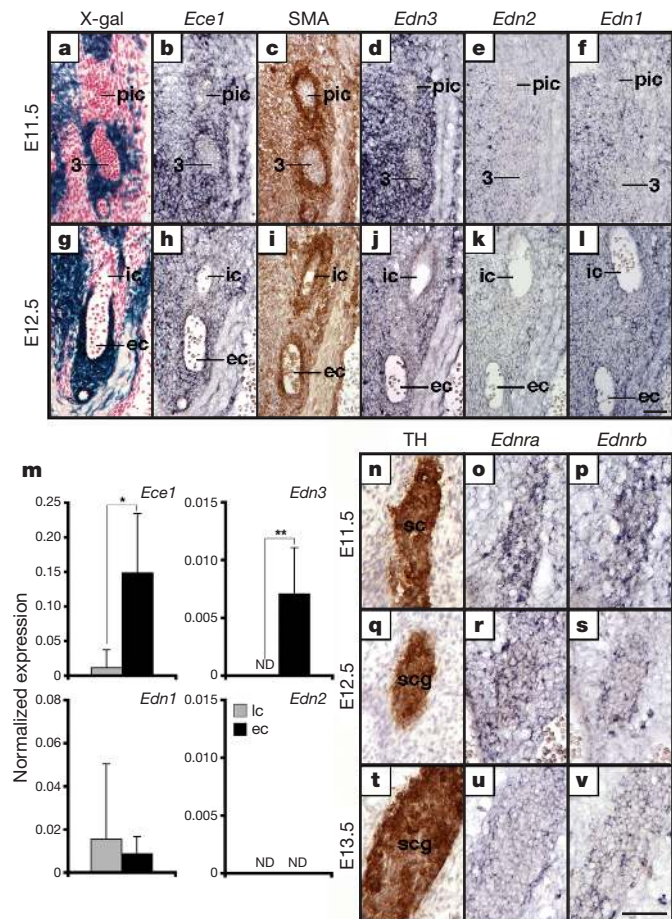
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axons, we next placed E12.5 SCG explants in proximity to beads soaked with endothelins. Human EDN3 seemed to be most effective in this regard (Fig. 3b, middle, and Supplementary Fig. 3b), although EDN1 and EDN2 also promoted directional outgrowth (data not shown). Moreover, when beads soaked with a high concentration of EDN3 were placed adjacent to SCG explants, random or undirected outgrowth was observed in addition to directional outgrowth (Fig. 3b, right). Thus, axonal outgrowth is a concentration-dependent and possibly gradient-dependent process. To determine which endothelin receptor mediates this response, we treated E12.5–E13.5 SCGs with EDN3 in the presence or absence of endothelin-receptor-selective antagonists. The EdnrA antagonist BQ123 (ref. 12) completely eliminated SCG neurite outgrowth, whereas the EdnrB antagonist BQ788 (ref. 13) was ineffective (Fig. 3c, upper row, and Supplementary Fig. 3c). In contrast, outgrowth from the Xth cranial (CNX/vagal)

ganglia explants, which express both endothelin receptors (data not shown), was selectively blocked by the EdnrB antagonist (Fig. 3c, lower row, and Supplementary Fig. 3d). We conclude that EDN3–EdnrA signalling is a potent mediator of SCG neurite outgrowth *in vitro*.

We next asked whether endothelins govern axonal guidance decisions of sympathetic neurons as they encounter the choice of projecting to either the internal or the external carotid arteries *in vivo*. For these experiments, SCG axonal projections in mice harbouring null mutations in genes encoding endothelin signalling components were assessed. Although EDN2 can promote axonal extension *in vitro*, *Edn2* is not expressed in vascular smooth muscle, and *Edn2*-null mouse embryos exhibited normal SCG axonal growth along both the internal and the external carotid arteries (data not shown). Similarly, *spotting lethal* mutant rat embryos, which carry a loss-of-function mutation in the *EdnrB* gene¹⁴, also displayed normal SCG axonal projections (Supplementary Fig. 4). Thus, consistent with our



ganglia explants, which express both endothelin receptors (data not shown), was selectively blocked by the EdnrB antagonist (Fig. 3c, lower row, and Supplementary Fig. 3d). We conclude that EDN3–EdnrA signalling is a potent mediator of SCG neurite outgrowth *in vitro*.

in vitro results, EdnrB is not required for directed SCG axonal extension. *Ece2* mutant embryos¹⁰ also exhibited normal SCG axonal outgrowth (data not shown). In contrast, *Ednra* mutant embryos¹⁵ exhibited a complete lack of SCG axonal extension along the external carotid arteries (Fig. 4c, i). This axonal projection deficit is specific for the external carotid arteries; *Ednra* mutants exhibited normal SCG axonal projections along the internal carotid arteries (Fig. 4a, b, g, h). The axonal projection defect in *Ednra* mutants is not due to defective smooth muscle cell differentiation, as shown by SMA staining (Fig. 4d–f, j–l). *Edn3* serves as a ligand that promotes EdnrA signalling in this context because *Edn3* mutant embryos¹⁶ showed a similar although slightly less severe phenotype compared to that of the *Ednra* mutants, in which SCG axons failed to fully extend along the external carotid arteries (Fig. 4o, r). In *Edn3* mutants, SCG neurons did extend some processes around the carotid bifurcation, albeit to a much lesser extent than littermate controls, and they initiated a small and poorly developed projection along the proximal section of the external carotid arteries. Even at E15.5, the latest time point analysed, axonal projections from the SCG along the external carotid arteries and their branches were markedly deficient in *Edn3*^{-/-} embryos (Supplementary Fig. 5). We note that *Edn1* is also expressed in the vicinity of the developing SCG, and thus Edn1 may have some functional overlap with Edn3 to support modest SCG extension along the external carotid arteries. Moreover, as observed for the *Ednra* mutants, *Edn3*-null axons extended along the internal carotid arteries and their branches normally (Fig. 4m, n, p, q and Supplementary Fig. 5).

These *in vivo* and *in vitro* findings collectively implicate Edn3 as a vascular-derived sympathetic axon growth factor. We suggest that Edn3, released from the neural-crest-derived smooth muscle layer of the external carotid arteries, directs those SCG neurons destined to innervate the salivary glands to send axonal projections along the nascent external carotid arteries—the sole pathway to these end organs.

Interestingly, our analysis demonstrates that Edn3–EdnrA signalling is not required for projections to the internal carotid arteries. Because embryonic SCGs do not spontaneously exhibit axonal outgrowth, at least *in vitro*, we predict that other factors expressed by the mesoderm-derived smooth muscle layer of the internal carotid artery direct projections from the SCG towards this blood vessel. It is noteworthy that the smooth muscle layer of the external carotid arteries originates from the third pharyngeal arch neural crest. Moreover, endothelin signalling also contributes to development of additional third pharyngeal arch structures and other aspects of cardiovascular and craniofacial development¹⁵, all of which are also dependent on neural crest cell progeny. Furthermore, endothelin receptors are broadly and dynamically expressed in these and other neural crest derivatives. Thus, it will be of interest to ask whether endothelins serve as axonal growth and guidance cues for other neural projections associated with third pharyngeal arch structures and other neural crest derivatives, such as the thymus, thyroid, cardiac outflow tracts and various craniofacial structures. Likewise, endothelins are expressed in the brain and in a variety of mesoderm-derived tissues¹⁷ and, therefore, may serve as guidance cues for many distinct populations of developing neurons.

Our observations indicate that *Ednra* expression within the SCG is variegated, suggesting that only a subset of SCG neurons can respond to endothelins and project to the external carotid arteries. The basis of this endothelin receptor heterogeneity within the SCG is unknown; it may arise by stochastic events, by a form of lateral inhibition within the ganglion, or by predetermination within the neural crest sublineage that gives rise to SCG neurons. We do not yet know if EdnrA-positive neurons are also able to project to the internal carotid arteries although, clearly, EdnrA-negative neurons are unable to project to the external carotid arteries. Therefore, we suggest a model in which developing sympathetic neurons are predetermined to choose between distinct vascular trajectories, and are

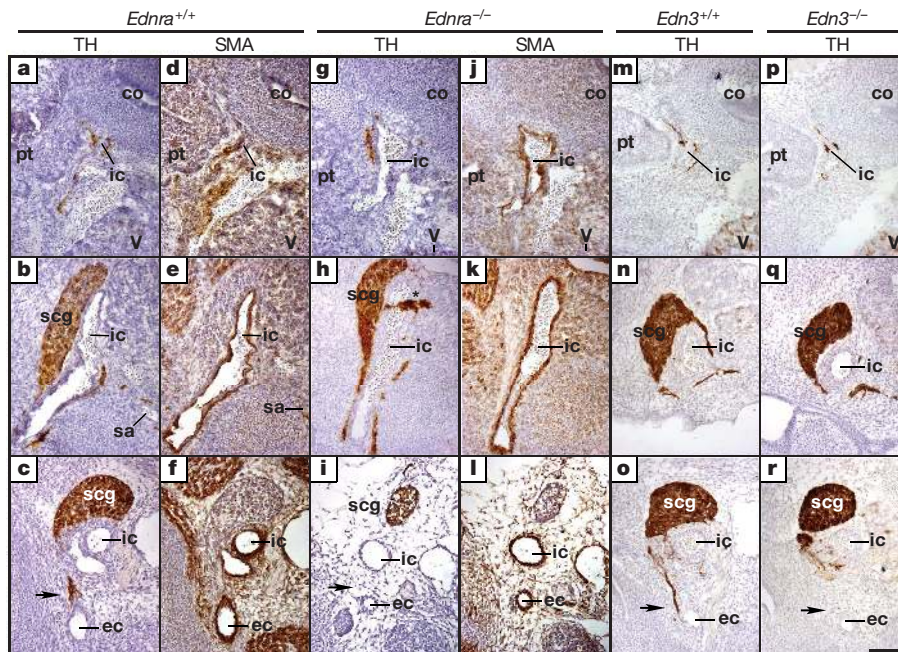


Figure 4 | Edn3 and its receptor EdnrA are essential for SCG axonal projections along the external but not internal carotid arteries in mouse embryos. **a–l**, Histological sections stained with TH or SMA from an E13.5 *Ednra*^{-/-} embryo and a littermate control. Three mutant embryos analysed from multiple litters exhibited a complete absence of axons along the external carotid artery, similar to the embryo shown in **g–l**. **m–r**, Histological sections from an E13.5 *Edn3*^{-/-} embryo and a littermate control stained with TH. Seven *Edn3*^{-/-} embryos analysed at E13.5 or older from multiple litters had defects in axonal projections towards the external carotid arteries. Sections shown in the top row are all at the cochlea–pituitary level, and show

the rostral projection from the SCG along the internal carotid artery. Shown in the middle row are sections at the level of the branch of the stapedia artery from the internal carotid artery; these reveal the cranial-most extent of the SCG and the initial projection from the SCG to the internal carotid artery. Sections in the lower row were taken at a level immediately above the bifurcation of the external and internal carotid arteries from the common carotid artery. Arrows point to the presence (in panels **c** and **o**) or the absence (in **i** and **r**) of axonal projections to the external carotid artery. Abbreviations: co, cochlea; pt, pituitary gland; V, trigeminal ganglion; *, histological artefact. Scale bar, 100 μ m.

thus destined to innervate select end organs. This choice of vascular route is guided, at least in part, by the actions of vascular-derived endothelins.

METHODS SUMMARY

The *Wnt1cre*¹⁸, *R26R*¹⁹, *Ednra*¹⁵, *spotting lethal*¹⁴, *Edn3* (ref. 16) and *Ece2* (ref. 10) alleles have been described previously. X-gal staining and SMA immunostaining of frozen sections were as described previously^{6,7}. Tyrosine hydroxylase (TH; Chemicon) immunoreactivity was visualized using an horseradish peroxidase (HRP)-conjugated secondary antibody and a diaminobenzidine (DAB) detection system. For *in situ* hybridization reactions, digoxigenin (DIG)-labelled antisense probes were generated for each gene, and the hybridization signal was detected using an alkaline phosphatase (AP)-conjugated anti-DIG antibody and 5-bromo-4-chloro-indolylphosphate/nitroblue tetrazolium (BCIP/NTB; Roche). For explant cultures, SCGs were cut into pieces on dissection, and placed into a collagen gel¹¹. Explants were grown in the absence or presence of endothelins (Alexis), endothelin- or BSA-soaked heparin-agarose beads (Sigma), or the endothelin receptor antagonists BQ123 or BQ788 (AG Scientific) in Leibovitz-L15(L15)-CO₂ medium supplemented with 5% fetal bovine serum (FBS) for three days.

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Information Microarray data referred to in this study have been deposited in the Gene Expression Omnibus (GEO, <http://www.ncbi.nlm.nih.gov/geo>) under the accession number GSE10360. Reprints and permissions information is available at www.nature.com/reprints. Correspondence and requests for materials should be addressed to D.D.G. (dginty@jhmi.edu).

METHODS

Histology and immunohistochemistry. Glutaraldehyde-fixed embryos were cryopreserved in sucrose. Five- or ten-micrometre cryosections were post-fixed, stained with X-gal by standard procedures, and counterstained with nuclear fast red. Glutaraldehyde- or paraformaldehyde-fixed embryos were cryopreserved and sectioned at 5- or 10- μm thickness for immunostaining. The primary antibodies used were TH (1:400; Chemicon) or alpha-smooth muscle actin (1:1,000; Sigma), and visualized using an HRP-conjugated secondary antibody and DAB/H₂O₂ detection system. For histological examination of sympathetic axonal phenotypes in mutant embryos, all cervical–thoracic sections were immunostained with TH. Alternatively, alternate sections from cervical to thoracic levels were subjected to hematoxylin–eosin staining and TH and SMA immunohistochemistry.

Microarray analysis. Vascular segments (the internal and external carotid arteries) were visualized by India ink injection into the left ventricle and dissected from 22 E13.5 mouse embryos, pooled, and total RNA extracted. Complementary RNAs, synthesized from complementary DNAs made from two rounds of amplification of each RNA sample, was used to hybridize and screen Affymetrix microarrays (MOE430_2) for differentially expressed genes by the JHMI Microarray Core Facility.

In situ hybridization. Histological sections from glutaraldehyde-fixed Wnt1-Cre/R26R embryos were used for *in situ* hybridization reactions. Digoxigenin-labelled sense and antisense probes were generated for *Ece1* (corresponding to nucleotides 2308–2532 of NM_199307), *Edn1* (834–988 of NM_010104), *Edn2* (747–851 of NM_007902), *Edn3* (1492–1713 of NM_007903), *Ednra* (565–991 of NM_010332) and *Ednrb* (1250–1563 of NM_007904), and the hybridization signal was detected using an alkaline-phosphatase-conjugated anti-digoxigenin antibody and BCIP/NTB (Roche).

Collagen gel culture. Vascular structures in E12.5 and E13.5 embryos were visualized by injection of India ink, and SCGs and CN Xs were dissected in PBS. SCGs were cut into several pieces and placed into a collagen gel as described previously¹¹. Explants were grown in the absence or presence of synthetic endothelins (EDN1, EDN2 or EDN3, Alexis), the endothelin receptor selective antagonists BQ123 or BQ788 (AG Scientific), or endothelin- or BSA-soaked heparin–agarose beads (Sigma) in L15CO₂ medium supplemented with 5% FBS for three days. Synthetic endothelins and receptor antagonists were applied at concentrations ranging from 1 nM to 100 nM and from 10 nM to 10 μM , respectively, to optimize assay conditions before performing the experiments. Neurite outgrowth was evaluated by immunostaining explants with anti-neurofilament (2H3) (1:150, Developmental Studies Hybridoma Bank) followed by immunofluorescence detection using fluorescein-conjugated secondary antibodies. To quantify neurite outgrowth, the length of neurites extending from explants was measured using an Image J image processing program.

Quantitative real-time PCR analysis. Vascular segments (the internal and external carotid arteries) were visualized by injection of India ink into the left ventricle and dissected from E12.5 mouse embryos. Total RNA was extracted from individual vascular segment by guanidinium isothiocyanate extraction and were reverse transcribed using standard conditions. All samples were analysed independently by real-time PCR using an iCycler iQ with SYBR green supermix (Bio-Rad).