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Contribution of Neural Crest-Derived Cells in the Embryonic and Adult Thymus

Katie Foster,* Julie Sheridan,‡ Henrique Veiga-Fernandes,* Kathleen Roderick,* Vassilis Pachnis,† Ralf Adams,§ Clare Blackburn,‡ Dimitris Kioussis,2* and Mark Coles2*§

Neural crest (NC)-derived mesenchyme has previously been shown to play an important role in the development of fetal thymus. Using Wnt1-Cre and Sox10-Cre mice crossed to Rosa26-YFP reporter mice, we have revealed NC-derived mesenchymal cells in the adult murine thymus. We report that NC-derived cells infiltrate the thymus before day 13.5 of embryonic development (E13.5) and differentiate into cells with characteristics of smooth muscle cells associated with large vessels, and pericytes associated with capillaries. In the adult organ at 3 mo of age, these NC-derived perivascular cells continue to be associated with the vasculature, providing structural support to the blood vessels and possibly regulating endothelial cell function.


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3 Abbreviations used in this paper: VEGF, vascular endothelial growth factor; α-SMA, α-smooth muscle actin; βAβ, benzyl alcohol and benzyl benzoate; E10.5–E18.5, days 10.5–18.5 of embryonic development; eYFP, enhanced yellow fluorescent protein; NCC, neural crest cell; NC, neural crest; PDGF, platelet-derived growth factor.

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To dissect the contribution of NC-derived cells in thymus development, we have used a tissue-specific heritable genetic labeling system. Thus, Cre recombinase was expressed under the control of either the Wntl (19) or Sox10 (20) promoter and regulatory elements, and Cre activity was reported via activation of a "silent" enhanced yellow fluorescent protein (eYFP), in which the eYFP gene preceded by a triple polyadenylation signal flanked by two loxP sites is knocked into the Rosa26 locus (21). As Wntl and Sox10 are expressed in the neural plate where NCCs originate (13, 20, 22), the latter cells will express Cre, thus deleting the transcriptional stop in front of the eYFP and indelibly marking these cells and their progeny by eYFP expression. We herein show that NC-derived cells that associate mainly with the thymic capsule at E12.5 enter the parenchyma before E13.5, remain there throughout gestation, and continue to be a major cellular component in the adult organ at 3 mo of age. Furthermore, we demonstrate that NC-derived cells differentiate into pericytes and smooth muscle cells, which are different cell subsets that form a supportive network for thymic blood vessels. Our results argue for a role of NC-derived cells that extends beyond the early stages of thymus organogenesis.

Materials and Methods

Mice

Wnt1-Cre (19), Sox10-Cre (20), Rosa26\textsuperscript{eYFP} (21), and C57BL/6 mice were bred at the animal facilities in the Medical Research Council–National Institute of Medical Research (U.K.). Embryos were generated by crossing Wnt1-Cre;Rosa26\textsuperscript{eYFP} mice with C57BL/6 females. All mice were bred and kept under specific pathogen-free conditions. Experiments were conducted according to the U.K. Home Office rules for animal experimentation.

Stereo microscopy

eYFP expression was analyzed using a Zeiss M2Bio (Carl Zeiss) stereofluorescent microscope. Images were acquired with an ORCA-ER (Hamamatsu) camera and Openlab software (Improvision). eYFP expression was analyzed using a wide-band GFP filter cube (470/500LP) (Kramer Scientific) with green (525) and red (630) filters (Chroma Technology). Images were merged in Openlab and contrast-enhanced in Photoshop (Adobe).

Whole-mount immunohistochemistry

Embryos and organs were fixed in 4% paraformaldehyde at 4°C and washed in 0.15% PBS-Triton-X100. Sections (100 μm) were made after embedding the fixed organs in 8% agarose and using a vibratome (Leica Microsystems). Tissues were washed and blocked in 10% serum and subsequently stained with Abs against eYFP directly conjugated to Alexa Fluor 488 (Invitrogen: Molecular Probes), endomucin (kind gift from Prof. D. Vestweber, desmin (Sigma-Aldrich), α-smooth muscle actin (α-SMA)-Cy3 (Abcam), PDGFR-α (R&D Systems), PDGFR-β (R&D Systems), BrdU (Abcam), and with appropriate secondary Abs against rat IgG (Alexa Fluor 594), mouse IgG (Alexa Fluor 594), and rabbit IgG (Alexa Fluor 594). Embryos negative for Cre resulting from Wnt1-Cre; Rosa26\textsuperscript{eYFP} × C57BL/6 breedings were stained with Abs detecting eYFP and used as negative controls. Background autofluorescence was collected by excitation with 488-nm laser and emission collected between 490 and 515 nm.

Frozen section preparation and staining

Tissues were embedded in OCT compound (Tissue-Tek), snap frozen on dry ice, and stored at −80°C. Sections were cut using a cryostat (Leica CM1900) at 10-μm thickness and collected onto poly-l-lysine-coated glass slides (VWR International). Sections were air dried for 2 min before being fixed for 2 min in 100% acetone (−20°C) and air dried for a further 20 min. Sections were blocked in 5% serum and subsequently stained with Abs against CD31 (BD Pharmingen) and PanK (Dako) and detected with appropriate secondary Abs: anti-rat IgG (Alexa Fluor 488) and anti-mouse IgG (Alexa Fluor 568). Slides were rinsed with water and air dried before mounting with VECTASHIELD HardSet mounting medium (Vector Laboratories).

Confocal microscopy

For detection of immunofluorescence, samples were analyzed using a Leica SP2 confocal or Leica AOB5 confocal microscope (Leica Microsystems). Tissue stained in whole-mount was optically cleared using benzyl alcohol and benzyl benzoate (BABB) (Sigma-Aldrich) before imaging. Confocal images are presented as single sections, as a merge of a number of serial sections, or as a three-dimensional rendering of many serial sections. Three-dimensional renderings were generated using Velocity software (Improvision).

Flow cytometric cell sorting

NCCs were analyzed by digesting the thymus with collagenase D (Roche) for 1 h at 37°C. The resulting single-cell suspension containing eYFP-expressing cells was stained with directly conjugated Abs against CD45 (eBioscience), MHC II (BD Biosciences), CD31 (eBioscience), and α-SMA; and mouse monoclonal anti-NG2 (Sigma-Aldrich) revealed with anti-mouse PE (eBioscience), biotinylated anti-mouse PDGFR-α (R&D Systems), and biotinylated anti-mouse PDGFR-β (R&D Systems) both revealed with APC- or PE-conjugated streptavidin. Before α-SMA staining, cells were fixed in 2% paraformaldehyde and permeabilized with 90% methanol. Samples were acquired on a FACSComp (BD Biosciences) and analyzed in FlowJo (TreeStar).

BrdU administration

Pregnant female mice were given one i.p. injection of BrdU (66 μg of mouse) at E13.5, E14.5, or E15.5. Embryos were recovered 2 days later and microdissected to remove the thymic rudiment. After fixation (4% paraformaldehyde), thymi were incubated with hydrochloric acid, washed with borate buffer before staining with an Ab recognizing BrdU, and analyzed by confocal microscopy.

Results

NC-derived cells in fetal and adult mice

To determine the pattern of eYFP expression in Wnt1-Cre; Rosa26\textsuperscript{eYFP} reporter mice, we have analyzed both embryonic and 3-mo-old mice by stereo and confocal microscopy. At E13.5, we show that eYFP is expressed in the craniofacial region (Fig. 1A, left) and in the neurons in the trunk of the embryo (Fig. 1A, left and right). In the thoracic cavity, eYFP expression is detected on the aorta and other arteries derived from the pharyngeal arches (not shown), as well as on the thymic rudiment (Fig. 1B). In the 3-mo-old mouse, eYFP-expressing cells are seen in craniofacial bones and tissues (Fig. 1C, left), as well as in peripheral nerves (Fig. 1C, right). Similar patterns of expression were observed in another reporter mouse in which eYFP is also expressed by NC-derived cells following Cre expression under the control of NC-specific promoter from the Sox10 gene (data not shown). This analysis showed that eYFP expression in tissues and organs from embryonic and 3-mo-old Wnt1-Cre;Rosa26\textsuperscript{eYFP} mice is restricted to NC-derived tissues, as previously described (18, 19, 23).

NC-derived cells in the fetal thymus

To follow the kinetics of colonization of the thymic rudiment by NC-derived cells, we examined the pattern of eYFP expression in Wnt1-Cre; Rosa26\textsuperscript{eYFP} reporter mice, and at E13.5, E15.5, and E17.5 embryos and newborn mice. At E13.5, some eYFP+ cells are present inside the thymus, but most are located at the capsule (Fig. 2A, left). At E15.5, eYFP+ cells are again found mainly at the capsule, but their frequency is increased inside the thymic rudiment, where they form trabeculae that appear to extend from the capsule into the parenchyma (Fig. 2A, middle). At E17.5, eYFP+ cells are still found at the periphery of the thymus, while those within the organ have organized into a three-dimensional network (Fig. 2A, right, Supplemental movie). Examination of sections from newborn Wnt1-Cre; Rosa26\textsuperscript{eYFP} thymi showed that eYFP+ cells are still present within the organ, with many associated with the capsule (Fig. 2B). No eYFP+ cells were
connective tissues surrounding the thymic blood vasculature in the NC-derived mesenchymal cells have been shown to contribute to perivascular cells before E13.5. NCCs are present within the organ and differentiate into (Fig. 2).

D-thymus occur mainly by NCC redistribution within the thymus axons. White arrow points to peripheral nerves. White arrow points to facial region. This suggested that the influx and increase of eYFP compared with the extensive incorporation seen in hemopoietic cells. like structures shows that cells expressing eYFP are found in as-

Most cells are associated with structures reminiscent of vascular embryonic or newborn thymus of nontransgenic mice (data not shown). Thus, we conclude that NC-derived cells enter the thymic rudiment before E13.5, remain there throughout gestation, and are still present in the newborn thymus.

To determine whether cells derived from the NC persist in the thymus beyond birth, we analyzed the distribution of eYFP cells in 3-mo-old Wnt1-Cre;Rosa26EYFP mice. eYFP-expressing cells are readily detectable in the adult thymus at this age, forming a three-dimensional network (Fig. 2C, left), with fewer cells being found at the capsule than at embryonic stages. High-magnification confocal analysis of thymus sections from 3-mo-old Wnt1-Cre;Rosa26EYFP mice by stereo microscopy. White arrow points to facial region. Right, Mice were further dissected to reveal expression of eYFP on peripheral nerves. White arrow points to axons.

chicken embryo (14). However, their precise function in the murine thymus remains controversial. To assess the kinetics of NC-derived cell contribution to connective tissue components such as perivascular cells, sections of thymic tissue at different stages of embryogenesis were stained with Abs recognizing markers specific for endothelial cells (CD31 and endomucin), pericytes (desmin), and smooth muscle cells (α-SMA). At E13.5, we found that CD31+ cells are already present throughout the thymic rudiment, indicating that endothelial cells, or endothelial precursor cells, are already present at this stage (Fig. 3A). Endomucin, thought to be expressed on mature endothelial cells (24), is not expressed until E15.5 (Fig. 3B). As mentioned above, a network of NC-derived cells is established in the organ by E13.5, and at this stage, eYFP+ cells express the pericyte marker, desmin (Fig. 3C). In contrast, α-SMA expression is not detected until after E15.5 when the formation of the blood vessel network is complete. From this stage onward eYFP+ cells also start expressing α-SMA (Fig. 3D).

NC-derived cells in the thymus express PDGF receptors

Cells with mesenchymal properties in the embryonic thymus have been reported to derive from NCCs (this report and Refs. 23, 25). PDGF receptor expression is characteristic of mesenchymal cells, and binding of PDGF mitogens regulates a number of processes including gene regulation and cell cycle control. To determine

NCCs are present within the organ and differentiate into perivascular cells before E13.5

NC-derived mesenchymal cells have been shown to contribute to connective tissues surrounding the thymic blood vasculature in the
which cellular compartments express PDGF receptors in the thymus, we analyzed the expression of PDGFR-α and PDGFR-β receptors on perivascular (NG2), endothelial (CD31), hemopoietic (CD45), and epithelial cell populations (MHC class II) in thymi from 3-mo-old C57BL/6 mice. We show that NG2 is expressed by 73.9 and 52.6%, CD31 by 11.7 and 10%, CD45 by 9.05 and 15.5%, and MHC class II by 6.6 and 18.7% of PDGFR-α/H11001 and PDGFR-β/H11001 populations, respectively (Fig. 4A). Thus, PDGFR-α and PDGFR-β are preferentially expressed by cells of a mesenchymal nature, including pericytes.

To determine whether NCCs are also involved in the PDGFR/PDGF axis of signaling during thymic development, we studied the expression of PDGFR-α and PDGFR-β in thymic eYFP+ cells from Wnt1-Cre;Rosa26eYFP mice, by flow cytometry. In one such analysis of E15.5 thymic rudiments, 63.1% of eYFP+ cells express PDGFR-α and 92.8% express PDGFR-β (Fig. 4B, left two panels). Interestingly, in the 3-mo-old thymus the majority (97.7%) of eYFP+ cells still express PDGFR-β, but PDGFR-α was found only on 9.2% of the cells (Fig. 4B, right two panels). This was confirmed by confocal microscopy, which showed that PDGFR-α is expressed only by eYFP+ cells found in the capsule of the 3-mo-old thymus, whereas PDGFR-β was expressed by eYFP+ cells found both at the capsule and within the organ (Fig. 4C).

FIGURE 3. Development of blood vessel and eYFP+ networks in embryonic thymus. A, Thymi from C57BL/6 embryos were dissected at E13.5 (left) and E15.5 (right) and stained with Abs recognizing pankeratin (green) and CD31 (red). Red arrows point to endothelial precursors; green arrows, epithelial cells. B–D, Thymi from Wnt1-Cre;Rosa26eYFP embryos were dissected at E13.5 (left column), E15.5 (middle column), and E17.5 (right column), processed as previously described, and stained with Abs recognizing eYFP (green), endomucin (red) (B), desmin (red) (C), and α-SMA (red) (D), and analyzed by confocal microscopy. White arrows point to capsule of thymic lobe; red arrows, vessels.

FIGURE 4. eYFP-expressing cells in the adult thymus express mesenchymal markers PDGFR-α and PDGFR-β. A, Thymi from 3-mo-old C57BL/6 mice were digested with collagenase, stained with markers recognizing perivascular cells (NG2), endothelial cells (CD31), hemopoietic (CD45), and epithelial cell populations (MHC class II) in thymi from 3-mo-old C56BL/6 mice. We show that NG2 is expressed by 73.9 and 52.6%, CD31 by 11.7 and 10%, CD45 by 9.05 and 15.5%, and MHC class II by 6.6 and 18.7% of PDGFR-α and PDGFR-β populations, respectively (Fig. 4A). Thus, PDGFR-α and PDGFR-β are preferentially expressed by cells of a mesenchymal nature, including pericytes.

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3186 IMAGING OF NEURAL CREST-DERIVED CELLS IN THE THYMUS

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Mutations that knockout the function of PDGFR-α often result in hypoplastic but functional thymi; however, the role of PDGFR-β signaling in the thymus is unknown. It has been shown that PDGFR-β is required for recruitment of pericytes to the walls of blood vessels. Indeed, embryos deficient for this receptor do not survive beyond birth due to sudden microvascular hemorrhaging and edema formation (9, 26). We herein show that in both the embryonic and 3-mo-old thymus, NC-derived cells are PDGFR-β⁺ (Fig. 4A), suggesting a mechanism by which NC-derived cells are recruited to the blood vasculature. However, by examining markers specific for pericytes and endothelial cells in E15.5 and E18.5 PDGFR-β-deficient embryos, we show that in the absence of this signaling receptor the thymic blood vasculature appears to have developed normally (Fig. 4D).

NC-derived cells are maintained in the thymus into adulthood

It has been suggested that beyond E17.5 in thymus organogenesis, NC-derived mesenchymal cells are lost or replaced. However, as shown in Fig. 2C, NC-derived cells are still detected in the 3-mo-old organ. To determine the character of the persisting NC-derived cells in the adult thymus, we examined the expression of markers for blood vessel endothelium, pericytes, and smooth muscle cells (as described above in Fig. 3) at 3 mo of age. We show that eYFP⁺ cells still surround endomucin-expressing endothelial cells (Fig. 5A), similar to the pattern observed in the embryonic thymus (Fig. 3). Because eYFP⁺ cells appear to surround vessel structures, we assessed the expression of markers associated with pericytes (desmin) and smooth muscle cells (α-SMA). We show that some vessel-associated eYFP⁺ cells also express desmin and, in separate stainings, α-SMA (Fig. 5, B and C). Identical patterns of expression were seen for endomucin, desmin, and α-SMA using another mouse strain (Sox10-Cre;Rosa26eYfp) that also expresses Cre in NC-derived cells and thus marks all NC derivatives with eYFP (Fig. 5D). Furthermore, flow cytometric analyses of Wnt1-Cre;Rosa26eYfp and Sox10-Cre;Rosa26eYfp thymi show that there is similar expression of the endothelial marker CD31 (0.065 and 2.93%), NG2 (98.8 and 98.5%), and α-SMA (16.2 and 23.4%, respectively) in these two reporter lines (Fig. 5E).

Age-related changes to the NCC contribution to the thymus

As the mouse ages, the perivascular space between the walls of the blood vessels and the surrounding cells in the thymus increases, and it is infiltrated with adipose tissue and lymphoid cells (27). This is correlated with a reduction in the export of new T cells into the periphery. To assess whether age-related atrophy is associated with a reduction in NC-derived cells, we have analyzed thymi from aged mice by both immunohistochemical stainings and flow cytometry. We show that at 9–10 mo of age, eYFP⁺ cells are still present within the thymus and continue to surround blood vessel structures, but there appears to be a reduction in the number that coexpress desmin and α-SMA (Fig. 6A). To confirm a decrease in the contribution of eYFP cells to the perivascular cell population during thymus organogenesis and aging, we analyzed thymi from mice at 9–10 mo of age by flow cytometry. We herein analyzed the percentage of CD31⁺, NG2⁺, and α-SMA⁺ cells that express eYFP. We show that the percentage of NG2⁺ cells that express eYFP decreases from 53.6% in the newborn thymus, to 42.5% at 3 mo of age, and to 4.57% by 9 mo of age. At birth the population of α-SMA⁺ cells that expresses eYFP is 24.1% of the total thymus, but there is an increase to 30.2% by 3 mo of age, indicating a differentiation or proliferation of existing eYFP⁺ cells in this compartment. Similar to the results seen by confocal microscopy in Fig. 6A, there is a decrease in α-SMA cells that express eYFP at 9 mo of age (21.3%) (Fig. 6B).

FIGURE 5. Differentiation of eYFP⁺ cells in the adult thymus. A–C, Thymi from 3-mo-old Wnt1-Cre;Rosa26eYfp mice were dissected, processed as previously described, and stained with Abs against eYFP (green), endomucin (red, (A) endomucin (red), (B) desmin (red), and (C) α-SMA (red), and analyzed by confocal microscopy. White arrows point to capsule of thymic lobe; red arrow, vessels. D, Thymi from 3-mo-old Sox10-Cre;Rosa26eYfp mice were dissected, processed as previously described, and stained with Abs against eYFP (green), endomucin (red, left), and α-SMA (red, right). White arrows point to capsule of thymic lobe; red arrow, vessels. E, Thymi from 12-wk-old Wnt1-Cre;Rosa26eYfp (top) and 6-wk-old Sox10-Cre;Rosa26eYfp (bottom) mice were digested with collagenase, stained with Abs recognizing endothelial cells (CD31), pericytes (NG2), and smooth muscle cells (α-SMA), and analyzed by flow cytometry. Cells were gated on eYFP⁺ expression, and the percentages of CD31⁺, NG2⁺, and α-SMA⁺ cells were calculated.

Taken together, these results show that NC-derived cells, which populate the thymus during organogenesis, persist in the adult thymus, having differentiated into at least two different cell types that form part of the same vascular supporting network. However, as
In 1975, Le Douarin and Jotereau (14) observed that the outer layer of the thymic capsule and connective tissues surrounding the blood vessels within the embryonic organ were derived from the neural crest. Using a transgenic reporter mouse line whereby LacZ expression is under the control of the Wnt1 promoter, more recent studies have followed the contribution of NC-derived cells in the thymus from early organogenesis to birth, and they show that beyond E17.5, NC-derived cells are rarely detected (17, 18). However, using eYFP as a reporter of Wnt1 expression, our data show that NC-derived cells do persist in the thymus beyond birth and remain there up to 9–10 mo of age. This apparent difference in expression of LacZ and eYFP, despite being under the control of the same promoter, may result from high CpG content in the LacZ gene and thus provide a predisposition to methylation-induced silencing (28). We herein show that in two independent mouse lines (Wnt1-Cre and Sox10-Cre), with each expressing Cre in a NCC pattern, eYFP⁺ cells are detected in the 3-mo-old thymus with identical distribution (around vessels) and characteristics (expressing desmin/NG2 and α-SMA). This makes it unlikely that eYFP expression is due to identical ectopic activation of the Cre gene.

In this report we describe different stages in blood vessel network development during fetal thymic differentiation. By E13.5, CD31⁺ endothelial cells are scattered within the thymic rudiment. At this stage eYFP⁺ cells form a network throughout the organ that is reminiscent of capillaries and that expresses the pericyte marker, desmin. Emergence of endothelial cells appears to coincide with NCC differentiation into perivascular cells, followed by mature blood vessel formation. However, the exact order of NCC and endothelial cell appearance in the thymic rudiment remains unclear. It is possible that endothelial precursor cells developing within the thymus attract NCCs into the rudiment and, subsequently, induce their differentiation into perivascular cells. It is equally possible that NC-derived cells enter the rudiment first and influence the migration of endothelial cells and the development of vascular networks, which in turn induce differentiation of NCCs into perivascular cells.

At E15.5, most NC-derived cells express PDGFR-β, and many also express PDGFR-α. Herein, we show that in the adult thymus at 3 mo of age, NC-derived cells present at the capsule still express both mesenchymal markers PDGFR-α and PDGFR-β. Furthermore, while NC-derived cells within the parenchyma down-regulate the expression of PDGFR-α, they maintain PDGFR-β expression (Fig. 4). This change in pattern of expression appears to coincide with the migration of NCCs into the thymus during embryogenesis and their differentiation into perivascular cells, suggesting a switch from their role in supporting epithelial cell proliferation (29) to a role in blood vasculature development. A similar down-regulation of PDGFR-α has also been observed during pericyte differentiation in the brain, indicating similarities in differentiation of NC-derived cells into perivascular cells both in the thymus and in the brain (30).

In mice deficient for PDGFR-α, a small number of thymi are hypoplastic due to a lack in epithelial cell proliferation, but they are functionally competent (31, 32). The ligand for this receptor, PDGF-B, is produced by endothelial cells, resulting in the recruitment of pericytes to the walls of blood vessels. In the absence of either PDGFR-β or PDGF-B there is a reduction in the number of perivascular cells associated with vessels, and there is a defect in endothelial cell proliferation. The function of PDGFR-β in thymus development has not previously been characterized. We herein show that in the thymus of PDGFR-β⁻/ⁿ⁻ embryos, thymic blood vascular development and perivascular cell recruitment to vessels appear normal, indicating that other molecules may be involved.
In summary, we have characterized the contribution of NC-derived cells in the embryonic and adult thymus (up to 9–10 mo of age) and their involvement in blood vessel formation. We showed that NC-derived cells enter the thymus before E13.5, are present throughout gestation, and remain associated with the adult organ. These cells differentiate into perivascular cells, which may contribute to a postulated thymus-blood barrier (33, 34), and may also provide structural support to vessels and regulate endothelial cell function. Thus, NC-derived cells are not only important for early thymus organogenesis, but they may also have an important role in blood vessel development and the function of the postnatal thymus.

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Disclosures

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