INTRODUCTION

Studies over the past 100 years have shown that blood cells develop in close proximity to the vascular system during embryogenesis. In mice, mesodermal cells, which have migrated from the primitive streak, form aggregates to establish blood islands in the yolk sac at around embryonic day 7 (E7). Over the next 12 hours, the central cells within the blood islands give rise to primitive blood cells, while the peripheral cells differentiate into endothelial cells. These blood islands subsequently fuse to form the first extra-embryonic vascular network. The close developmental association of the hematopoietic and endothelial cell lineages within the yolk sac of the developing embryo has led to the hypothesis that they arise from a common precursor, the hemangioblast (Sabin, 1920; Murray, 1932; Wagner, 1980).

Gene-targeting studies have demonstrated that FLK1 (Kdr – Mouse Genome Informatics), a receptor tyrosine kinase, and SCL, a basic helix-loop-helix transcription factor, are crucial for hematopoietic and endothelial cell development. In mouse embryos, Flk1 expression can be detected in the presumptive mesodermal yolk sac blood island progenitors as early as E7 (Yamaguchi et al., 1993; Dumont et al., 1995). Mice deficient in Flk1 do not develop blood vessels or yolk sac blood islands, and die between E8.5 and E9.5 (Shalaby et al., 1995). In chimeric aggregation studies with wild-type embryos, Flk1+/– ES cells fail to participate in vessel formation or to contribute to primitive or definitive hematopoiesis, suggesting that Flk1 inactivation results in cell autonomous endothelial and hematopoietic defects (Shalaby et al., 1997). Mice carrying homozygous mutations at the Scl locus die at around E10.5 because of defective embryonic hematopoiesis (Shivdasani et al., 1995; Robb et al., 1995). The requirement of Scl in adult hematopoietic system has been shown in chimeric mice generated by injecting Scl–/– ES cells into the wild-type blastocysts (Porcher et al., 1996). None of the hematopoietic cells in these chimeric mice developed from Scl–/– ES cells, suggesting a functional role for SCL in adult hematopoiesis. Subsequent studies have shown that vasculogenesis in the Scl–/– yolk sac occurs normally, but that remodeling of the primary vascular plexus is defective (Visvader et al., 1998; Elefanty et al., 1999).

The in vitro differentiation model of ES cells has proven to be valuable for studies of cell lineage development. Hematopoietic cells develop within embryoid bodies (EBs, in vitro differentiated ES cells) faithfully following in vivo developmental kinetics (Kennedy et al., 1997; Choi et al., 1998; Palis et al., 1999). As in the developing embryo, primitive erythroid cells develop prior to definitive hematopoietic populations (Keller et al., 1993; Palis et al., 1999). Endothelial
and selected with 500 μg/ml G418 and 2 μg/ml gancyclovir. G418 and FIAU resistant clones were picked after ~10 days of selection and expanded for further analyses.

We have previously demonstrated that BL-CFCs expressed FLK1 (Faloon et al., 2000) and that Scl<sup>-/-</sup> EBs failed to generate blast colonies, the progeny of BL-CFCs, in vitro (Faloon et al., 2000; Robertson et al., 2000). These studies suggest that Scl is crucial for hemangioblast development and that the hemangioblast can be identified as the FLK1<sup>+</sup>SCL<sup>-/-</sup> cell population. To understand better the relationship between FLK1 and SCL expression in the differentiation of hematopoietic and endothelial cell lineages, we have introduced a non-functional human CD4 gene (CD4) encoding extracellular and transmembrane domains into one allele of Scl. This strategy allows us to detect SCL-expressing cells by using monoclonal antibodies against human CD4 and flow cytometry analyses. Kinetic analyses of FLK1 and human CD4 expression in vitro differentiated Scl<sup>+/CD4</sup> ES cells and cell sorting experiments for hemangioblast, hematopoietic and endothelial cells demonstrated that hematopoietic and endothelial cells developed via the sequential generation of FLK1- and SCL-expressing cells.

In this paper, CD4 refers to the non-functional human CD4 gene/protein.

**MATERIALS AND METHODS**

**Construction of the Scl-human CD4 knock-in targeting vector and isolation of the knock-in clones**

The 5' homology arm containing ~7.4 kb BamHI to NotI DNA fragment was isolated from the Scl 2A genomic clone. The extracellular and transmembrane domain of the human CD4 (CD4) gene (kindly provided by Dr Kenneth Murphy at Washington University) was knocked-in in-frame into the NotI site of the exon IV. This NotI site is 10 nucleotides downstream of the initiation codon. The 3' homology arm containing ~4 kb NotI to SalI DNA fragment was isolated from the Scl 2A genomic clone. The 3' arm was first blunt ligated into the XhoI site located downstream of the PGK-neomycin cassette of the pLNTK. The 5' homology-CD4 fragment was blunt ligated into the SalI site of the pLNTK/3' homology arm. The targeting construct also contains a thymidine kinase gene. R1 ES cells were electroporated with a linearized SCL targeting vector construct and selected with 500 μg/ml G418 and 2 × 10<sup>6</sup> M gancyclovir (FIAU). G418 and FIAU resistant clones were picked after ~10 days of selection and expanded for further analyses.

**ES differentiation, blast colony and hematopoietic replating**

Mouse ES cells were maintained on STO feeder cells in the presence of leukemia inhibitory factor (LIF). EBs were generated as described (Kennedy et al., 1997; Choi et al., 1998). Blast colonies were generated by replating sorted CD4<sup>+</sup> cells from day 2.75-3 EBs in the presence of VEGF (5 ng/ml), kit ligand (KL, 1% conditioned medium or 100μg/ml purified) and D4<sup>T</sup> endothelial cell conditioned medium (CM) (Kennedy et al., 1997; Choi et al., 1998) at 25%. Erythroid and myeloid colony assays were carried out as described previously (Faloon et al., 2000). Briefly, cells sorted from day 6 and day 8 EBs were cultured in methyl cellulose containing 10% plasma-derived serum (PDS, Antech; Texas), 5% protein free hybridoma medium (PFHM2, Gibco/BRL), ascorbic acid (12.5 μg/ml), L-glutamine (2 mM), transferrin (300 μg/ml; Boehringer Mannheim) and MTG (4.5×10<sup>-4</sup> M), together with the following cytokines: KL (1% conditioned medium), IL3 (1% conditioned medium), Epo (2 units/ml), IL1 (5 ng/ml) IIL6 (5 ng/mI), G-CSF (30 ng/ml), M-CSF (5 ng/ml) and GM-CSF (3 ng/ml). Hematopoietic colonies were counted 7-10 days later. IL1, IL6, IL11, G-CSF and M-CSF were purchased from R&D Systems. KL was obtained from a medium conditioned by CHO cells transfected with a KL expression vector (kindly provided by Genetics Institute). Epo was purchased from Amgen (Thousand Oaks, CA), and IL3 was obtained from a medium conditioned by X63 Ag8-653 myeloma cells transfected with a vector expressing IL3 (Karasuyama and Melchers, 1988).

**FACS analysis**

For FACS analysis of FLK1 and CD4 expression, EBs were treated with 7.5 mM EDTA/PBS (pH 7.4) for 2 minutes. Cells were centrifuged, resuspended in staining medium (4% FCS in PBS), passed through a 20-gauge needle to generate single cell suspension, and counted. After centrifugation, cells were resuspended to a density of 5 × 10<sup>6</sup> cells/ml in 2.4G2 supernatant to block antibodies from binding to Fc receptors II and III (CD16 and CD32) (Unkeless, 1979). Cells were placed into each well of a V-shaped 96-well plate at 5 × 10<sup>6</sup> cells/well followed by incubation on ice for 30 minutes. Subsequently, biotinylated mouse anti-human CD4 monoclonal antibody (CALTAG), freshly diluted in wash buffer (4% FCS in PBS), was added into each well and incubated on ice for 15 minutes. After three washes, freshly diluted streptavidin-allophycocyanin (SAv-APC; Pharmingen) and phycoerythrin (PE)-conjugated anti-FLK1 monoclonal antibody (Pharmingen) were added and incubated on ice in the dark for 15 minutes. Cells were washed three times, resuspended in wash buffer, and transferred to 5 ml polypropylene tubes for analysis. A three-color FACS analysis of FLK1, human CD4 and endothelial or hematopoietic markers was carried out by staining cells first with endothelial/hematopoietic markers. FITC-conjugated anti-mouse CD31, FITC-conjugated anti-mouse CD34 or FITC-conjugated anti-mouse CD45 was added directly. When cells were stained with non-labeled anti-mouse VE-cadherin and anti-mouse Ter-119 antibodies, FITC-conjugated goat anti-rat IgG and FITC-conjugated goat anti-rat IgG<sub>2b</sub>, respectively, were used to amplify the signals. All the antibodies were purchased from Pharmingen. Cells were subsequently stained with anti-human CD4 and anti-FLK1 antibodies as described above. Cells were analyzed on a FACS Caliber (Becton-Dickinson). FACS data were analyzed with CellQuest software (Becton-Dickinson).

**Cell sorting and in vitro cultures of sorted cell populations**

For FACS-cells sorting, single cell suspensions were prepared the same way as the FACS analyses, except that the EB cells were dissociated with trypsin (0.08%)/EDTA (0.36 mM)/PBS instead of 7.5 mM EDTA/PBS. Double-color staining and sorting for FLK1 and human CD4 cells were performed the same way as for FACS analysis. Prior to sorting, stained cells were filtered through 40-μm nylon mesh. Cells were sorted using FACS MoFlo (Becton-Dickinson), and the sorted cells were reanalyzed on a FACS Caliber. FLK1<sup>CD4<sup>-<sup></sup></sup></sup> or FLK1<sup>CD4<sup>+</sup></sup>CD4<sup>+</sup> sorted cells were cultured for an additional 20-48 hours in a bacterial petri dish in IMDM media containing 15% pre-selected FCS, ascorbic acid (50 μg/ml), L-glutamine (2 mM) and MTG (4.5×10<sup>-4</sup> M) at a cell density of 2×10<sup>7</sup>/ml.

**Endothelial cell cultures and immunohistochemical staining**

Cells sorted from day 6 EBs were plated onto type IV collagen...
Clones with the correct targeting event were expanded and colonies picked and screened by Southern blot analyses (Fig. 1). ES cells were electroporated, selected, and individual FLK1–CD4– cells (from day 2.75 EBs), reverse transcribed, and poly-adenylated using terminal transferase. Total cDNA was amplified using 32P randomly primed cDNA probes corresponding to the 3′ end of the L32, Flk1, Slc, Gata1, Gata2 and Lmo2 genes. After the hybridization, the blot was washed at high stringency and exposed to an X-ray film.

In situ hybridization

Sorted CD4+ and CD4- cells, from day 5 EBs, were fixed in freshly prepared 4% paraformaldehyde in PBS. Cells were dehydrated through graded ethanol, xylene and embedded in paraffin wax. Sections (4 µm) were adhered to Superfrost Plus (VWR) microscope slides. Sections of ES mouse embryos were placed on the slides and served as positive controls for Slc expression (Silver and Palis, 1997). In situ hybridization was performed essentially as described (McGrath et al., 1999), except probes were synthesized at 4.2 × 106 dpm/µg, and hybridization occurred at 50°C. Replicate slides were probed with a sense control probe and no signal above background was detected (not shown). Cells were photographed in brightfield and darkfield with a SPOT RT slider (Diagnostic Instruments) digital camera. Images were processed, pseudocolored and merged using Photoshop (Adobe Systems) and Fovea Pro 2 (Reindeer Graphics).

Gene expression analysis

RNA was purified from sorted FLK1+CD4+, FLK1+CD4-, and FLK1–CD4– cells (from day 2.75 EBs), reverse transcribed, and poly-A tailed using terminal transferase. Total cDNA was amplified using oligo dT as a primer (5′GTTAACTCGAGAATTCT3′) (Brady et al., 1990). After one round of re-amplification using 1µl of the primary PCR products as template, PCR products were separated by agarose gel electrophoresis, transferred to a nylon membrane, and hybridized with 32P randomly primed cDNA probe corresponding to the 3′ end of the L32, Flk1, Slc, Gata1, Gata2 and Lmo2 genes. After the hybridization, the blot was washed at high stringency and exposed to an X-ray film.

RESULTS

Construction of human CD4 knock-in ES cells at the Slc locus

To isolate SCL-expressing cells, we introduced a non-functional human CD4 gene encoding extracellular and transmembrane domains (Bedinger et al., 1988) into one allele of Slc. The strategy for constructing a targeting vector is illustrated in Fig. 1. As shown, a CD4-LoxPNeo cassette was targeted in-frame into the NotI site of the fourth exon of Slc. The restriction enzyme, NotI, site is located 10 nucleotides downstream of the ATG initiation codon. As a result, Slc expression is disrupted, and CD4 expression in the modified cells should faithfully mimic the endogenous Slc expression. R1 ES cells were electroporated, selected, and individual colonies picked and screened by Southern blot analyses (Fig. 1). Clones with the correct targeting event were expanded and karyotyped. Karyotypically normal clones (clones 1-4, 1-19 and 1-68) were further subjected to in vitro analyses.

Kinetics of the development of FLK1 and CD4-expressing cells during EB differentiation

To establish that CD4 expression truly correlates with that of Scl, we first sorted CD4+ and CD4- cells and subjected them to in situ hybridization for Slc expression. As shown in Fig. 2, the sorted CD4+ cells showed strong hybridization to Slc antisense probe (Fig. 2A-D), while CD4- cells were negative for Slc expression (Fig. 2E-H). The levels of Slc expression in the sorted CD4+ cells are similar to the endogenous levels in blood island cells of the E8.5 mouse embryo (Fig. 2I). These studies indicate that CD4 expression can be used as a surrogate marker for Slc expression.

After CD4+ cells were shown to represent SCL expressing cells accurately, kinetic analyses of CD4 and Slc expression were performed using in vitro differentiated Slc+/CD4+ ES cells. Undifferentiated ES cells do not express Slc or SCL (Choi et al., 1998; Falloon et al., 2000). Upon differentiation, cells expressing Slc developed first in EBs and CD4-expressing cells were detected from day 2.75 in developing EBs (Fig. 2J), although the levels of CD4 expression at this stage were low. The low CD4 expression in early EBs could reflect the weak Slc promoter activity in early development and is consistent with studies by Elefanty, who characterized knock-in mice carrying a lacZ gene at the Slc locus (Elefanty et al., 1998; Elefanty et al., 1999). Cells expressing CD4 increased significantly over the next 24-48 hours (Fig. 2J). About 40% of the total EB cells expressed CD4 by day 5, and ~75% of the total EB cells expressed CD4 by day 6. The percentage of CD4+ cells decreased thereafter and reached to ~20% by day 8. At earlier time points (days 2.75-3), the all CD4+ cells also expressed Slc. EBs from days 4-6 contained three distinct cell populations as follows: cells expressing only Slc (FLK1+CD4+), cells expressing only CD4 (FLK1+CD4+), and cells expressing both Slc and CD4 (FLK1+CD4+). In later EBs (day 8), the number cells expressing both Slc and CD4 was significantly lower, and there were predominantly FLK1+CD4+ or FLK1+CD4+ cells.

Developmental relationship between FLK1+CD4-, FLK1+CD4+ and FLK1+CD4- cell populations

FACS analysis for FLK1 and CD4 expression suggested that FLK1+ cells developed first followed by CD4+ cells. To understand the relationship between FLK1+CD4+, FLK1+CD4- and FLK1+CD4- cells, we first FACS-sorted FLK1+ and FLK1- cells from day 2.5 EBs and then cultured them separately for an additional 20 hours. FLK1+ cells progressed to give rise to FLK1+CD4+ cells after 10 hours of in vitro culture, and FLK1+CD4- cells were readily detected after 20 hours of culture. FLK1- cells progressed first to FLK1+ and then to FLK1+CD4+ cells with time (Fig. 3A). We subsequently FACS-sorted FLK1+CD4+ and FLK1+CD4- cell populations from day 4 EBs, cultured them for an additional 20 hours, and analyzed them for FLK1 and CD4 expression. As shown in Fig. 3B, FLK1+CD4+ cells readily gave rise to FLK1+CD4+ cells, indicating that FLK1 is downregulated within the FLK1+CD4+ cells to generate FLK1+CD4- cell populations. Consistently, FLK1+CD4- cells first gave rise to FLK1+CD4+ and then to FLK1+CD4- cells.
upon an additional 20-hour culture. FLK1−CD4+ cells further increased after 48 hours of culture (not shown). These studies clearly argue that there is a distinct, developmental succession between FLK1−CD4−, FLK1−CD4+ and FLK1−CD4+ cells. The FLK1−CD4+ cell population will initially develop. The Scl gene will be turned on within the FLK1−CD4+ cells to give rise to the FLK1−CD4+ cell population. Subsequently, the Flk1 gene will be downregulated within the FLK1−CD4+ cells to finally give rise to the FLK1−CD4+ cells.

**FLK1+SCL+ cells from day 2.75 EBs are enriched for the hemangioblast**

As discussed earlier, BL-CFCs express FLK1 (Faloon et al., 2000) and Scl−/− EBs fail to generate blast colonies that are the progeny of BL-CFCs (Faloon et al., 2000; Robertson et al., 2000). To determine if the BL-CFC cell population could be identified as FLK1+SCL+, day 2.75 EB cells were subjected to FACS analysis and cell sorting. If FLK1 and SCL are true determinants of the hemangioblast, it was expected that FLK1+CD4+ cells were enriched for BL-CFCs. Therefore, FLK1+CD4+, FLK1+CD4− and FLK1−CD4− cells from day 2.75 EBs were sorted and subjected to blast colony assays. As shown in Fig. 4A, blast colonies developed predominantly from sorted FLK1+CD4+ cells, not FLK1+CD4− or FLK1−CD4− cells. The small number of blast colonies that developed from FLK1−CD4+ cells is most likely to be due to the CD4low cells that could have been sorted as a negative cell population. Furthermore, secondary EBs mainly developed from FLK1−CD4− cells, strongly supporting the idea that FLK1−CD4− cells still contained undifferentiated ES cells.

To characterize further the FLK1+CD4+, FLK1+CD4− and FLK1−CD4− cells present within day 2.75 EBs, they were also subjected to gene expression analyses. RNA from FLK1+CD4+, FLK1+CD4− and FLK1−CD4− cells was subjected to global amplification of mRNA transcripts (Brady et al., 1990). The amplified PCR products were analyzed for

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**Fig. 1.** Generation of human CD4 (CD4) knock-in ES cells. (A) Targeting strategy used to insert CD4 gene into the Scl locus is shown. The mouse Scl locus, targeting construct, and the targeted allele are shown. The black boxes and numbers below indicate the exons. The ATG codon starts within exon IV. (B) Southern blot analysis of the targeted allele. DNA was digested with enzymes indicated and run on an agarose gel. Top left, genomic DNA was digested with EcoRI and probed with genomic DNA as indicated below. Both targeted and wild-type alleles generated a 5.2 kb DNA band. Top right: genomic DNA was digested with EcoRI and probed with exon 6 probe as indicated below. The wild-type allele (upper band) and the targeted allele (lower band) are shown. Bottom: genomic DNA was digested with MunI and probed with human CD4 gene. Only the targeted allele gave 7.3 and 3 kb DNA bands. The gel was run for 48-72 hours for good separation of DNA. The enzymes used are as follows: X, XhoI; B, EcoRI; N, NcoI; B, BamHI; H, HindIII; M, MunI.
the expression of Flk1, Scl, Gata1, Gata2 and Lmo2 (Fig. 4B). As expected, Flk1 was expressed within FLK1+CD4– and FLK1+CD4+ cells. Scl, Gata1, Gata2, and Lmo2 expression was greatly raised within FLK1+CD4+ cells compared with FLK1+CD4– cells. None of these genes was expressed in FLK1–CD4+ cells. Taken together, our results strongly support the notion that hemangioblasts can be identified as FLK1+SCL+ cells.

**FLK1 and SCL expression in hematopoietic and endothelial cells**

To determine if FLK1 and SCL expression can define hematopoietic and endothelial cell populations, the nature of FLK1+CD4–, FLK1+CD4+, and FLK1+CD4+ cell populations, present in later stages of EB development (days 5-6), was determined by three-color FACS analyses for FLK1, CD4 and hematopoietic or endothelial cell markers. Cells gated on VE-cadherin+, CD31+ (PECAM-1+), CD34+, Ter-119+, or CD45+ were analyzed for FLK1 and CD4 expression. As shown in Fig. 5, cells expressing VE-cadherin, an endothelial cell marker, expressed both FLK1 and CD4, while cells expressing Ter119, an erythroid marker, expressed CD4 but not FLK1. CD31 and CD34, markers of both hematopoietic and endothelial cells, were expressed in both FLK1+CD4+ and FLK1–CD4+ cells. CD45, a marker normally used for hematopoietic cells, was expressed in both FLK1+CD4+ and FLK1–CD4+ cells at day 6.

**Fig. 2.** (A–I) In situ hybridization of Scl. CD4+ and CD4– cells were sorted from day 5 EBs and subjected to in situ hybridization. (A–D) CD4+ cells; (E–H) CD4– cells; (I) E8.5 yolk sac. bi, blood islands; e, endoderm. (J) Kinetic analyses of FLK1 and SCL expression during EB development. In vitro differentiated ES cells (from day 2.75 to day 8) from wild-type R1 and three independent knock-in clones (1–4, 1–19, and 1–68) were subjected to FACS analyses for FLK1 and SCL expression. Numbers in a given box indicate the percentage of cells that are FLK1+CD4+, FLK1+CD4+, and FLK1+CD4+ cells.
**Fig. 3.** In vitro progression of hematopoietic and endothelial cell lineages. (A) FLK1<sup>+</sup>CD4<sup>+</sup> and FLK1<sup>+</sup>CD4<sup>+</sup> cells were FACS-sorted from day 2.5 EBs and further cultured in vitro. The cells were then analyzed for FLK1 and CD4 expression for up to 20 hours. The cells at 0 hour indicate the starting cell population after sorting. (B) FLK1<sup>+</sup>CD4<sup>+</sup> cells were FACS-sorted from day 4 EBs and further subjected to in vitro culture as in A. The cells were analyzed for FLK1 and CD4 expression for up to 20 hours. The cells at 0 hours show the sorting purity.

**Fig. 4.** FLK1<sup>+</sup>CD4<sup>+</sup> cells from D2.75 EBs are enriched for the hemangioblasts. (A) FLK1<sup>+</sup>CD4<sup>+</sup>, FLK1<sup>+</sup>CD4<sup>+</sup> and FLK1<sup>+</sup>CD4<sup>+</sup> cells were FACS-sorted and subjected to blast colony replating (6x10<sup>4</sup> cells/ml). The resulting blast colonies were counted 4 days later. Secondary EBs were also counted and shown. Error bars indicate standard deviations from triplicate plates. (B) Gene expression analysis. RNA from FLK1<sup>+</sup>CD4<sup>+</sup>, FLK1<sup>+</sup>CD4<sup>+</sup> and FLK1<sup>+</sup>CD4<sup>+</sup> cells were amplified and probed with Flk1, Scl, Gata1, Gata2, Lmo2 and L32. 1, unsorted 2.75 EBs; 2, FLK1<sup>+</sup>CD4<sup>+</sup>; 3, FLK1<sup>+</sup>CD4<sup>+</sup>; 4, FLK1<sup>+</sup>CD4<sup>+</sup>; 5, water – a negative control for RT-PCR.
CD45 was predominantly expressed in FLK1-CD4+ cells from later stages of EBs (day 8, not shown).

To ascertain if hematopoietic and endothelial progenitors can be isolated based on SCL and FLK1 expression, we FACS-sorted FLK1+CD4- FLK1-CD4+ and FLK1-CD4+ cells from day 6 EBs, and subjected them to hematopoietic and endothelial cell assays. For the hematopoietic progenitor studies, sorted cells were replated in methylcellulose cultures with hematopoietic factors. As shown in Fig. 6A, hematopoietic progenitors developed from both FLK1+CD4+ and FLK1-CD4+ cells. FLK1-CD4+ cells predominantly gave rise to erythroid colonies, while FLK1+CD4+ cells gave rise to macrophage and bi-potential erythroid/macrophage colonies. The endothelial progenitors were assayed by replating sorted cells onto type IV collagen-coated plates with VEGF and cultured for 4 days. Afterwards, the adherent cells were stained for CD31. As shown in Fig. 6B, endothelial cells developed from FLK1+CD4+ and FLK1-CD4+, but not from FLK1-CD4- cells. No adherent cells developed from FLK1-CD4+ cells.

Fig. 6C, all the hematopoietic colonies developed from FLK1-CD4+ cells, while the endothelial cells still developed from FLK1-CD4- cells (not shown). Taken together, we conclude that hematopoietic progenitors initially develop from FLK1+CD4+ and FLK1-CD4+ cells and then from FLK1-CD4+ cells in later stages of EBs.

**DISCUSSION**

We have examined the expression of FLK1 and SCL by using the in vitro differentiation model of Scl+/CD4+ ES cells to further understand the development of hemangioblast, endothelial and hematopoietic cell progenitors. Our studies demonstrate that almost all the CD4+(SCL+) cells from day 2.75 EBs co-expressed FLK1 (Fig. 2I). Furthermore, sorted FLK1+CD4+ cells, but not FLK1+CD4-, readily generated blast colonies. Finally, gene expression analyses demonstrated that the expression of Scl, Gata1, Gata2 and Lmo2, genes to be expressed in primitive hematopoietic compartment, was greatly enriched in FLK1+CD4+ cells compared with FLK1+CD4- cells. Taken together, these studies indicate that FLK1+SCL+ cells present within day 2.75 EBs represent the hemangioblasts. In zebrafish, SCL is expressed in the lateral...
mesoderm, which gives rise to hematopoietic, endothelial and pronephric lineages (Gering et al., 1998). Cells expressing both FLK1 and SCL appear to give rise to FLK1-SCL+ hematopoietic and FLK1-SCL- endothelial cells (Gering et al., 1998). These observations predict that cells expressing both SCL and FLK1 represent hemangioblasts. Indeed, cells expressing both SCL and FLK1 increase dramatically when SCL is overexpressed in zebrafish embryos (Gering et al., 1998). As a result, both hematopoietic and endothelial cells also increase. The suggestive role for SCL in the specification of the hemangioblast formation comes from the observation that the expansion of FLK1-SCL+ cells occurs at the expense of somitic and pronephric duct tissues (Gering et al., 1998). Furthermore, SCL expression is greatly reduced in zebrafish cloche (clo) mutants (Liao et al., 1998), which show defective hematopoietic and endothelial differentiation (Stainier et al., 1995). More importantly, ectopically expressed SCL can rescue, although incompletely, the hematopoietic and endothelial cell defects in these mutants. Additionally, Drake and Fleming (Drake and Fleming, 2000) have examined early mouse embryos for FLK1 and SCL expression. At E6.5, FLK1-SCL+ cells were already present, albeit dispersed, in the extra-embryonic yolk sac. Primary vascular networks became evident in the regions where FLK1-SCL+ cells were detected, suggesting that the initial FLK1-SCL+ cells represent hemangioblasts.

The analyses of sorted cell populations have demonstrated that FLK1+ cells isolated from day 2.5 EBs progressed to give rise initially to FLK1+CD4+ cells and subsequently to FLK1-CD4+ cells. Consistently, sorted FLK1+CD4- cells from day 4 EBs progressed to give rise to FLK1+CD4+ and then to FLK1-CD4+ cell populations when cultured for an additional 24-48 hours in vitro, while FLK1+CD4+ cells proceeded to give rise to FLK1-CD4+ cells. As the hematopoietic progenitors were present within FLK1-CD4+ and FLK1+CD4+ cells in early EBs (day 4-6) and in FLK1-CD4+ cells in later EBs (day 8, Fig. 2), we conclude that FLK1 expression within hematopoietic progenitors is downregulated (Fig. 7).

Fig. 6. Hematopoietic and endothelial cell lineage development. (A) Day 6 EB cells were sorted for FLK1+CD4-, FLK1+CD4+, FLK1-CD4+ and FLK1-CD4- and subjected to hematopoietic replating (5x10⁴ cells/ml). The hematopoietic colonies were counted after 5-7 days. Ery, erythroid; Mac, macrophage; Ery+Mac, bi-potential erythroid and macrophage colony. (B) FLK1+CD4-, FLK1+CD4+, FLK1-CD4+ and FLK1-CD4- cells sorted from day 6 EBs were cultured on type IV collagen coated plates for 4 days in the presence of VEGF (50 ng/ml). Four days later, the adherent cells were stained with PECAM1 (CD31) antibodies (right) or just treated with secondary antibody alone (left). FLK1-CD4+ cells did not generate any adherent cells (not shown). (C) Day 8 EBs were sorted for FLK1+CD4-, FLK1+CD4+ and FLK1-CD4+ cells and subjected to hematopoietic replating (5x10⁴ cells/ml). The colonies were counted 5-7 days later.
Consistent with this interpretation, there were only FLK1^{+}CD^{4}^{-}/CD^{4}^{+} cell populations present in later stages of EBs (day 8). Previous studies have also demonstrated that hematopoietic progenitors were enriched within the FLK1^{+} cell populations derived from early EBs, but not later stages of EBs (Kabrun et al., 1997). Similarly, the FLK1^{+} cell population from E8.5 yolk sacs and whole embryos contained hematopoietic progenitors, while few FLK1^{+} cells present in day 12 fetal livers contained hematopoietic potential (Kabrun et al., 1997). Elefanty and colleagues knocked-in a bacterial lacZ gene to the Scl locus to follow SCL-expressing cells (Elefanty et al., 1998; Elefanty et al., 1999). Histological staining of Scl^{+}/lacZ embryos for β-galactosidase activity showed that lacZ was expressed in hematopoietic and endothelial cells, as well as in the developing brain. Cell sorting and replating studies of β-galactosidase^{+} cells from fetal livers showed that erythroid and myeloid progenitors were present within β-galactosidase^{+} cells. Furthermore, β-galactosidase^{+} cell fractions from the bone marrow were enriched for erythroid, myeloid, lymphoid and CFU-S12 progenitors. These studies support the notion that SCL is expressed in hematopoietic progenitors, which could also include hematopoietic stem cells.

Our studies have also demonstrated that the development of endothelial cells can be followed by FLK1 and SCL expression (Fig. 7). Replating studies have demonstrated that endothelial cells developed from two distinct cell populations, FLK1^{+}CD^{4}^{-} and FLK1^{+}CD^{4}^{+} cells. The nature of the endothelial cells developing from the FLK1^{+}CD^{4}^{-} and FLK1^{+}CD^{4}^{+} cells is currently not known. Given the findings that vascular development occurs normally in Scl^{−} embryos, but that subsequent vascular remodeling is defective in these embryos (Visvader et al., 1998), it is possible that FLK1^{+}CD^{4}^{+} derived endothelial cells represent terminally differentiated mature endothelial cells. In avian systems, it has been well demonstrated that different mesodermal regions produce endothelial progenitors (Pardanaud et al., 1996). The somatopleurual mesoderm, adjacent to the ectoderm, will give rise only to endothelial cell populations. The splanchopleurual mesoderm, adjacent to the endoderm, will give rise to both hematopoietic and endothelial cells. Given these observations, it is possible that endothelial cells that develop closely together with hematopoietic cells will express Scl, while endothelial cells that do not associate with hematopoietic cells will not express Scl. Further studies are required to address these issues.

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*Fig. 7.* Schematic diagram of the hematopoietic and endothelial cell lineage development within EBs.


