Development of both human connective tissue-type and mucosal-type mast cells in mice from hematopoietic stem cells with identical distribution pattern to human body

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The transplantation of primitive human cells into sublethally irradiated immunodeficient mice is the well-established in vivo system for the investigation of human hematopoietic stem cell function. Although mast cells are the progeny of hematopoietic stem cells, human mast cell development in mice that underwent human hematopoietic stem cell transplantation has not been reported. Here we report on human mast cell development after xenotransplantation of human hematopoietic stem cells into nonobese diabetic severe combined immunodeficient (NOD/SCID)/γcnull (NOG) mice with severe combined immunodeficiency and interleukin 2 (IL-2) receptor γ-chain allelic mutation. Supported by the murine environment, human mast cell clusters developed in mouse dermis, but they required more time than other forms of human cell reconstitution. In lung and gastric tract, mucosal-type mast cells containing tryphtase but lacking chymase located on gastric mucosa and in alveoli, whereas connective tissue-type mast cells containing both tryphtase and chymase located on gastric submucosa and around major airways, as in the human body. Mast cell development was also observed in lymph nodes, spleen, and peritoneal cavity but not in the peripheral blood. Xenotransplantation of human hematopoietic stem cells into NOG mice can be expected to result in a highly effective model for the investigation of human mast cell development and function in vivo. (Blood. 2004;103:860-867)

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Introduction

Mast cells are recognized as the principal cells which initiate immunoglobulin E (IgE)-dependent immediate hypersensitivity and as the cells which contribute to innate immunity and tissue remodeling.1-2 There are 2 phenotypically distinct mast cell subpopulations in rodents: connective tissue-type mast cells (CTMCs) and mucosal-type mast cells (MCCs). These populations differ in location, cell size, staining characteristics, ultrastructure, mediator content, and T-cell dependency.3 Proliferation of rodent MCCs is dependent on T-cell–derived cytokines,4 whereas that of CTMCs is supported by stem cell factor (SCF). In humans, mast cells are distinguished on the basis of their protease composition;5,6 MCCT contains tryptase and chymase in its granules and is predominant in skin and intestinal submucosa, like CTMCs in rodents. MCCT also contains tryptase, but lacks chymase, and is predominant in the alveolar wall and gastric mucosa, similar to MCCs in rodents. Human mast cells were reported to develop only under the influence of SCF, but T-cell–derived interleukin 3 (IL-3) has little effect on their differentiation.7 Recently, human intestinal mast cells were reported to respond to IL-3 by enhancing their growth,8 but SCF is still an indispensable factor for human mast cells. Mast cells are the progenies of hematopoietic stem cells (HSCs).9,10 In mice, the progenitor cells capable of becoming mast cells leave the bone marrow and enter the circulation but complete their differentiation into mast cells only after arriving in peripheral tissues such as lung, bowel, and skin.10-11 Unfortunately, the developmental mechanism of human mast cells remains far less clear, possibly because the lack of an appropriate in vivo assay system.

The transplantation of primitive human cells into immunodeficient C.B-17-Prkdexcid (scid)12,13 and into NOD/Lisz-scid or NOD/Shi-scid (nonobese diabetic severe combined immunodeficient [NOD/SCID]) mice14,15 is thought to constitute an appropriate functional in vivo system for human HSCs. However, it has been suggested that residual natural killer (NK) cell activity in NOD/SCID mice might interfere with engraftment.16,17 Recently, we developed NOD/SCID/γcnull (NOG) mice by backcrossing IL-2 receptor γ-chain deficient (γcnull) mice to NOD/scid mice.18 Compared with NOD/SCID mice treated with anti-NK cell antibody17 and NOD/SCID/β2 microglobulinnull mice,19,20 both of which were established for reducing residual NK cell activity, the newly developed NOG mice were superior in terms of efficiencies of human HSC engraftment, because they lack NK cell activity and show reduced interferon γ production from dendritic cells.18 In addition, human CD3+ T cells can be generated and matured from human HSCs in NOG but not in other mice.21,22 These results encouraged us to check human mast cell development in NOG.
mice, even though there are no reports of mast cell development after human HSC transplantation into mice.

This is, therefore, the first report of human mast cell development in mice after transplantation of human HSCs, with NOG mice as recipients. Moreover, development of human mast cells in NOG mice was supported by the murine environment, and, depending on their protease compositions, the distribution of human mast cells was similar to that in the human body.

Materials and methods

Mice, human cell preparation, and xenotransplantation

NOG mice were established at the Central Institute of Experimental Animals (Kawasaki, Japan) by backcrossing γc−/− mice to NOD/Shi-scid mice, as reported previously.28 The mice were shipped to the animal facility of Kyoto University (Kyoto, Japan) and kept under specific pathogen-free conditions in accordance with the facility’s guideline.

Human cord blood was collected from healthy full-term deliveries after obtaining informed consent. Mononuclear cells were isolated on Ficoll-Hypaque (Pharmacia, Uppsala, Sweden) after phagocyte depletion with silica (ImmunoBiological Laboratories, Gunma, Japan).23 CD34+ cells were further isolated by using AutoMACS (Miltenyi Biotec, Bergisch Gladbach, Germany). After the enrichment, assessment of their fractions were further isolated by using AutoMACS (Miltenyi Biotec, Bergisch Gladbach, Germany). After the enrichment, assessment of their purity by flow cytometry showed that approximately 95% of the cells were CD34+ cells. In the experiments using lineage-depleted cells (lin−/CD34+ cells), cord blood mononuclear cells were treated with StemSep (Stem Cell Technologies, Vancouver, Canada), followed by CD34+ selection.

Xenotransplantation of purified human cells into NOG mice was also described previously.19,21 Mice were irradiated at 8 to 12 weeks of age with 240 cGy. Enriched CD34+ cells (50 000) were injected intravenously through the tail vein. After the transplantation, mice were given sterile balanced salt solution containing 1% fetal calf serum was injected into the peritoneal cavity to carefully open the peritoneal cavity. The peritoneal cavity was carefully opened, and the fluid containing peritoneal cells was collected with a pipette. One part of the collected cell suspension was used for direct counting of living cells, and the remaining cells were used for staining with toluidine blue or with safranin-O and Alcian blue on the cytospin preparations and for cytometry. On the cytospin preparation, a proportion of the positively stained cells among the 200 nucleated cells was determined.

Immunohistochemistry

To detect human mast cells, acetone-fixed frozen sections were blocked with donkey serum before incubation with antihuman CD45 mAb (Nichirei, Tokyo, Japan) and then incubated with Cy3-conjugated 2nd Ab (Jackson, West Grove, PA). FITC-conjugated avidin bound to mast cells,26,27 and Hoechst 33342 (Molecular Probes, Eugene, OR). Specificity of avidin binding to mast cells was confirmed with both human and mouse tissue preparations from skin, lung, and gastric stomach.

We used acetone-fixed frozen sections for chymase, because the routinely used Carnoy solution reduces the number of chymase+ cells.28 Antihuman chymase mAb (Chemicon, Temecula, CA) labeled slides were stained with alkaline phosphatase (AP)-conjugated 2nd Ab (Vector, Burlingame, CA). For tryptase, formalin-fixed paraffin-embedded sections and methanol-fixed cytospin preparations were incubated with antitryptase mAb (Chemicon) and with AP-conjugated 2nd Ab. The color was developed with naphthol AS-Bi/new fuchsin. In some experiments, biotin-conjugated antichymase mAb-labeled cells were incubated with horseradish peroxidase–conjugated streptavidin, and the color was developed with 3-amoine-9-ethylcarbazole (Vector). The cells were sequentially labeled with AP-conjugated antitryptase mAb, and the color was developed with fast blue substrate (Vector). We used healthy parts of skin obtained after mastectomy as positive controls.

For SCF distribution in NOG mouse skin, we sequentially incubated acetone-fixed frozen sections with antimouse SCF polyclonal Ab (R&D Systems, Minneapolis, MN) and Cy3-conjugated 2nd Ab (Jackson) and observed with a confocal laser microscopy (Olympus).

RNA purification and RT-PCR (reverse transcription–polymerase chain reaction)

Cellular total RNA was isolated with the phenol/guanidine isothiocyanate method using a Trizol reagent (Invitrogen) and reverse-transcribed to complementary (cDNA) with oligo dT primers and SuperScript Synthesis System (Invitrogen). Reaction mixtures were amplified with 0.2 U Taq polymerase (Sigma) using 25 cycles for glyceraldehyde-3-phosphate dehydrogenase (G3PDH) and 40 cycles for others under the following conditions: denaturation at 95°C for 30 seconds, annealing at 55°C for 30 seconds, and extension at 72°C for 30 seconds. Oligonucleotide primers for SCF which recognized both human and mouse SCF, 5'-TCTTACGCT-GCTCTCAATTT-3' and 5'-ACTACAGCTGCATGATC-3', human tryptase, 5'-GGAAACCACCATTTGTAGCAG-3' and 5'-ATTACCTTTGCACACAGGG-3'; and human chymase, 5'-AAGGAGAAAGCCGACTGACCC-3' and 5'-TCCGACCCTTCATAGGATACG-3' were synthesized.

To evaluate the species origin of SCF, PCR products were purified with the QIAquick PCR purification kit (Qiagen, Valencia, CA) and digested for 1 hour with restriction enzymes, XmaI and Nsil. Mouse keratinocyte Pamm212 and human keratinocyte DJM-1 were positive controls.

Human mast cell culture in vitro

Human cord blood CD34+ cells were cultured in AIM-V medium (Invitrogen) with either human SCF (Amgen, Thousand Oaks, CA) or murine SCF (Kirin Brewery, Gunma, Japan) at concentration of 10 ng/mL (suboptimal) or 100 ng/mL (optimal), as described previously but with a minor modification.29-31 During the first week, 50 ng/mL human IL-6 (Kirin Brewery) was also added. Flow cytometry at the constant flow rate was used to assess viable cell number with propidium iodide and mast cell percentage with anti-Kit mAb.

Statistical analysis

Data are presented as the mean ± SD values. Statistical significance was determined with the Student t test, and P < .01 was considered significant.
Results

Murine mast cell distribution in NOG mice

Compared with age-matched control B6 mice, the dermis of 12-week-old NOG mice (n = 6) has a normal concentration of mast cells (Figure 1A-B), but, surprisingly, in the skin of 20-week-old NOG mice (n = 6), we observed a substantial number of toluidine blue+ cells in the upper dermis (Figure 1C-D). The pathologic findings also showed epidermal hyperplasia.

Murine mast cells collected from the peritoneal cavity were safranin+ CTMCs, as from the dermis. The number of peritoneal mast cells from 12-week-old NOG mice (0.51 ± 0.07 × 10⁶ cells/mouse, mean ± SD values from 6 mice) was not different from that from control B6 mice (0.49 ± 0.05 × 10⁶ cells/mouse). Although peritoneal mast cells in B6 mice had a tendency to increase in number as the mice became older, 20-week-old NOG mice had significantly fewer peritoneal mast cells (0.28 ± 0.05 × 10⁶ cells/mouse) than did 20-week-old B6 mice (1.02 ± 0.57 × 10⁶ cells/mouse, n = 6) (p < .01). Figure 1E shows toluidine blue staining of the mesentry from 20-week-old NOG mice, and Figure 1F shows safranin-O staining of peritoneal cells, also from 20-week-old NOG mice.

In addition, we checked mast cells in lung and gastric tract, where MMCs were predominantly distributed. The lungs showed no mast cell at the alveoli (Figure 1G) but a few mast cells, which were safranin+ CTMCs, around major airways (Figure 1H). In the gastric stomach, mast cells were distributed in both submucosa and mucosa (Figure 1I-K). Mast cells in the submucosa were safranin+ CTMCs (arrowheads in Figure 1J), whereas unexpectedly safranin-negative, Alcian blue+ MMCs were identified in gastric mucosa (arrows in Figure 1L,K), even though NOG mice lack T cells because of \( \gamma^{null} \) mutation. The number of mast cells in the lung and gastric tract of the control B6 mice and the older NOG mice had not changed.

In NOG mice, lymph nodes could hardly be identified without human HSC transplantation: only 2 lymph nodes at the axillaries and one at the mesenteric region of 6 mice. Pathologic examination of these identified lymph nodes showed a small number of mast cells located in the connective tissue at the capsule and an even smaller number of mast cells at the trabecula of the lymph node, and none in the cortex or medulla (Figure 1L). They were all safranin+ CTMCs (data not shown). In spleen of NOG mice, mast cells were present in the connective tissue of the trabecula, as shown with arrows in Figure 1M. Again, they were all safranin+ CTMCs (data not shown). Except for the ease of finding lymph nodes from control B6 mice, the number and histologic distribution of mast cells in lymph nodes and spleen of 12-week-old NOG mice were not different from those of the control B6 mice and the older NOG mice.

Human mast cell development in mouse skin

Four weeks after transplantation of cord blood CD34+ cells, human CD45+ cells were detected in NOG mouse peripheral blood, in which CD34+ myeloid cells were predominant, and CD19+ B cells and CD56+ NK cells were also present (Figure 2). Human CD45+ cells gradually increased, and 12 weeks after transplantation, we also observed abundant human CD3+ T cells in NOG mice, in agreement with previous study.18

To identify mast cell development after human CD34+ cell transplantation into NOG mice, we first tried to detect tryptase and chymase messenger RNA (mRNA) expression in the skin. Four weeks or 8 weeks after xenotransplantation (n = 3), this expression was hardly detectable. Twelve weeks after the transplantation (n = 3), however, human mast cell-specific protease expression was identified in NOG mouse skin (Figure 3A). At this time, chymase mRNA was more prominent than tryptase mRNA.

In addition, we stained skin sections with antihuman CD45 mAb, which did not react to NOG mice not receiving transplants (data not shown). Four weeks or 8 weeks after xenotransplantation (n = 3), unexpectedly we observed human CD45+ cells mainly in

![Figure 1. Murine mast cell distribution in NOG mice.](image-url)

(A-D) Toluidine blue staining of the skin of NOG mice. Thin frozen sections from 12-week-old (A-B) and 20-week-old (C-D) NOG mice were stained with acidic toluidine blue. Arrows in the picture from 12-week-old NOG mice (A) indicate metachromatically stained cells. The upper dermis of 20-week-old NOG mice shows bandlike proliferation of toluidine blue+ cells and hyperplasia of epidermis. Magnification, × 200 (A,C) and × 400 (B,D). (E) Toluidine blue staining of mesentery of 20-week-old NOG mice, and arrows indicate mast cells. Magnification × 200. (F) Safranin-O staining of peritoneal cells obtained from 20-week-old NOG mice. Magnification, × 400. (G-H) Alcian blue and safranin-O staining in Carnoy fixed preparations from 20-week-old NOG mice. In lung, a few safranin+ CTMCs were recognized around major airways (H), whereas safranin-negative, Alcian blue+ MMCs were not observed in alveoli (G). In the gastric stomach, NOG mice showed safranin+ CTMCs in the submucosa (arrowheads in I and image with hypermagnification in J), and safranin-negative, Alcian blue+ MMCs in mucosa (arrows in I and image with hypermagnification in K). Magnification, × 100 (G-I), × 200 (H), and × 400 (J-K). (L-M) Toluidine blue staining of Carnoy fixed preparations from lymph node (L) and spleen (M) from 20-week-old NOG mice. Mast cells located only at the capsule of the lymph nodes. In the spleen, a few mast cells were present as shown with arrows in M. Magnification, × 200 (L-M).
than 2% of the cells were human CD45, in which CD33/H11001

Four weeks after the transplantation, less

NOG mice after HSC transplantation.

with Hoechst 33342). Arrows indicate human CD45
cells (yellowish green with FITC-avidin), and nuclei (blue

tissue sections of NOG mouse skin 12 weeks (B) and 20 weeks (C) after the

fixation and stained for human CD45 (red

cells, which are stained orange. Magnification,

200. (D-F) Human MC specific chymase+/H11001
cells in the mouse skin. Acetone-fixed frozen sections of NOG mouse skin 24 weeks after the transplantation were stained with

human chymase+mAb. Human chymase+/H11001
cells proliferated focally in the upper dermis (e), represented by the

bar bellows, whereas in other lesions on the same samples nonstained granulated cells were located in the

upper dermis (f). Magnification, × 12.5 (D) and × 200 (E-F). (G) The number of chymase+/H11001 human mast cells and nonstained granulated mouse mast cells in NOG mouse skin 24 weeks after the transplantation. The number of human and mouse mast cells supported by mouse dermis was almost identical. Bar graphs display mean ± SD values from 5 different preparations.

the upper dermis and some in the basal layer of the epidermis.

However, none of these human CD45+ cells were positive for FITC-avidin, indicating they were not mast cells. Twelve weeks

transplantation (n = 8), finally we could detect a small

number of avidin-FITC and human CD45 double-positive mast
cells in the dermis (Figure 3B). Then, the number of double-

positive human mast cells gradually but focally increased to

produce clusters in the dermis of NOG mice (Figure 3C).

Next, we checked the presence of human mast cell-specific

tryptase and chymase by immunohistochemical staining. Staining the

skin of NOG mice not receiving transplants with antihuman

chymase mAb showed no positive cells, confirming that there was

no cross-reaction to mouse mast cells (data not shown). More than

12 weeks after xenotransplantation into NOG mice, we recognized

human chymase+ cells focally in the dermis, and after 24 weeks

(n = 6), some mast cell clusters consisted of more than 100 human chymase+ cells (Figure 3D-E). The number and size of the clusters

consisting of chymase+ cells in NOG mouse skin differed even

among the specimens obtained from the same mouse. As shown in

Figure 3E, in some areas of NOG mouse skin, proliferated mast cells consisted of only chymase+ human mast cells but not murine mast cells. We counted the mast cells in the area under 500 μm of skin surface and above the sebaceous gland of the dermis and found that the number of human mast cells in the area consisting of only chymase+ cells (38.0 ± 8.4 cells/500 μm, mean ± SD values from 5 different preparations) and that of mouse mast cells in the area consisting of only nonstained granulated cells (39.8 ± 3.9) was almost the same 24 weeks after the transplantation (Figure 3G).

At the same time, we recognized cells showing strong positive

reaction for human tryptase in the upper dermis of NOG mice on

the formalin-fixed preparations. These cells were recognized only

more than 12 weeks after xenotransplantation (data not shown).

Differentiation into mast cells from HSCs

to confirm de novo generation of human mast cells from HSCs, we transplanted lineage-depleted cells into NOG mice and analyzed

the skin, lung, and stomach 4, 8, 12, and 20 weeks after the

transplantation (n = 3 for each time point). But the time course of

mast cell development in those tissues after transplantation with

lin−/CD34− cells was the same as that with whole CD34+ cells.

Human mast cell development supported by mouse SCF

To identify what kind of environment that supports human mast
cell development in NOG mouse skin, we examined SCF production. Restriction enzymes could identify the species origin of amplified PCR-products: NsI cut human products to 137 and 425 base pairs (bp), whereas NsiI cut murine products to 257 and 305 bp (Figure 4A). Although mast cells themselves can produce SCF,32 and we actually detected SCF derived from in vitro–cultured human mast cells, digestion of PCR products suggested that murine SCF was dominant in the skin of NOG mice even when human mast cells had been reconstituted after the successful transplantation of human CD34+ cells (Figure 4B). We got the same results
under the esophagus (data not shown). In gastric stomach, we could
around major airways (Figure 6B) and in the submucosal tissue
lung (n = 3 to 12 cells, was observed in the frontal section of the unilateral
Human chymase /H11001
stronger than that of chymase mRNA in lung. (Figure 6A). In contrast to the skin, the intensity of tryptase mRNA was
chymase mRNA in lung and gastric stomach of NOG mice (Figure
6A). In bone marrow, most of these CD203c+ cells also strongly expressed Kit (CD117), suggesting they were human mast cells. A
small portion of Kit-negative and IL-3 receptor α-chain (CD123)
weakly positive cells were also observed in CD203c+ cells,
suggesting the presence of human basophils. However, all CD203c+
cells in the peripheral blood were negative for Kit but expressed
IL-3 receptor, indicating that human basophils were reconstituted
from the transplanted human CD34+ cells and circulated in NOG
mice (n = 4).

Bone marrow and peripheral blood

Although neither tryptase+ cells nor toluidine blue+ cells could be
detected on smear preparations periodically obtained from bone
marrow and peripheral blood (data not shown), analysis of more
than 20,000 cells by flow cytometry identified a small number of
CD203c+ cells in human CD45+ cells from the bone marrow (3.4% in
human CD45+ cells) and peripheral blood (1.2% in human
CD45+ cells) 20 weeks after the xenotransplantation (Figure 7A).

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mice (n = 4).

Lung and gastric stomach

To determine human mast cell development in organs other than
skin, we examined lung and gastric stomach, where MC_T
was dominant in humans. Twelve weeks after transplantation of human
cord blood CD34+ cells, we could detect both tryptase and
chymase mRNA in lung and gastric stomach of NOG mice (Figure
6A). In contrast to the skin, the intensity of tryptase mRNA was
stronger than that of chymase mRNA in lung.

Although murine MMCs were sensitive to formalin and invisible
on formalin-fixed preparations before the transplantation (data
not shown), in the formalin-fixed specimens from lung 20 weeks
after xenotransplantation, a small number of toluidine blue+ cells,
3 to 12 cells, was observed in the frontal section of the unilateral
lung (n = 4). In sequential sections, we confirmed most of the
toluidine blue+ cells were strongly positive for human tryptase.
Human chymase+ cells were seen only in the connective tissue
around major airways (Figure 6B) and in the submucosal tissue
under the esophagus (data not shown). In gastric stomach, we could

Figure 4. SCF expression in the mouse skin. (A) Control study for PCR and
restriction enzymes. Templates from human DJM-1 and mouse Pam212 keratinocytes
were amplified after PCR and then digested with Xmal and Nal. Human SCF
products were cut to 137 and 425 bp and mouse SCF products to 257 and 305 bp. KC
indicates keratinocytes. (B) Human mast cell development in NOG mouse skin was
predominantly supported by mouse SCF. Expected 562-bp bands were observed
after PCR reaction. The digestion patterns with Xmal and Nal suggested the main
source of SCF in the skin was mouse-derived SCF even after the xenotransplanta-
tion. 1 indicates NOG mouse not receiving transplant; 2, NOG mouse 12 weeks after
xenotransplantation; 3, in vitro–derived cultured human mast cells from cord blood;
and 4, negative control. The findings were similar when cDNA template from NOG
mouse skin was used 8 weeks and 20 weeks after the transplantation. (C) Mouse
SCF protein distribution in the NOG mouse skin. SCF localized in a physiologically
cytoplasmic pattern in the epidermis. Magnification × 400.

Figure 5. Mouse SCF effectively supports human mast cell development in vitro.
Human cord blood CD34+ cells were cultured with suboptimal (10 ng/mL) and
optimal (100 ng/mL) doses of recombinant SCF. The number of mast cells (C) after 6
weeks of culture was assessed in terms of the total number of the viable cells (A) and
the Kit+ percentage (B) determined by flow cytometric analysis. Bar graphs display
mean ± SD values from 3 independent experiments.
Human mast cell and basophil development from the transplanted human CD34 blood, peritoneal cells, and spleen from NOG mice after HSC transplantation.

Peritoneal cavity and mesentery

The 2.1 ± 0.5 × 10⁶ cells collected from the NOG mouse peritoneal cavity 20 weeks after the transplantation contained 3.9% ± 1.2% safranin⁺ CTMCs (n = 4). On the cytopsin preparation from the collected peritoneal cells, we failed to detect chymase⁺ human mast cells (data not shown). Flow cytometry showed that less than 0.9% of the collected peritoneal cells expressed human CD45⁺ mast cells (Figure 7C). Among these human CD45⁺ cells, 2.1% expressed CD203c (0.02% of all peritoneal cells), which were human Kit⁺ mast cells.

In the mesentry of NOG mice 20 weeks after the transplantation, we recognized a small number of human mast cell clusters consisting of 2 to 6 chymase⁺ cells (Figure 8A).

Lymph nodes and spleen

Twenty weeks after the transplantation, when human lymphocytes had already been reconstituted, only a small number of human mast cells (0 to 4 cells in the frontal section, n = 4) was identified in the lymph nodes. They were located at the trabecula and comprised human chymase⁺ connective tissue type mast cells (Figure 8B). Abundant human chymase⁺ cells could be identified extensively in the red pulp but not in the white pulp of the spleen of NOG mice (n = 4) by immunochemistry (Figure 8C). These cells did not form clusters in the spleen. As shown in Figure 7D, flow cytometry confirmed the abundant presence of human mast cells as CD203c and Kit double-positive cells (9.8% in human CD45⁺ cells and 3.3% in all spleen cells).

Discussion

Most of our studies concerning mast cells have used rodent cells. However, rodent and human mast cells show lots of heterogeneities. Their dependence on growth factors is different, and the contents of secretory granules are also different. In particular, both types of human mast cells located in the mucosa and submucosa contain heparin, whereas murine MMCs lack heparin, resulting in their sensitivity to formalin. Thus, rodent mast cells are not always a suitable model for studying mast cells under the physiologic and pathologic condition in humans. The established SCF-dependent human mast cell cultures from HSCs in cord blood, fetal liver, peripheral blood, and bone marrow provide new opportunities for mast cell research. By using in vitro–cultured human mast cells, we have been able to identify several new aspects of human mast cells, for example, the effect of IL-4 on human mast cell growth factors.

In the study presented here we show for the first time human mast cell development in mice after xenotransplantation. Twenty weeks after xenotransplantation, we noticed the cluster formation of human mast cells, in which sometimes more than 100 human mast cell-like cells were present. This finding suggests that human mast cells in xenotransplanted mice can develop in vivo as functional cells similar to rodent mast cells.
chymase+ mast cells were reconstituted in the dermis of NOG mice. The question arises why human mast cells developed in NOG mice, although those derived from transplanted human HSCs have never been found in other mice. In our opinion, NOG mice have, first of all, a strong capacity for human cell engraftment, as various kinds of blood cells, including T cells, were reconstituted after xenotransplantation.21 Second, NOG mice may provide a suitable environment for mast cells, as dramatic mast cell proliferation was observed in the dermis of 20-week-old mice. Mast cell hyperplasia was recently reported in γδ T-cell–deficient mice with NOD background,43 which means that mast cells in NOG mice may proliferate by being liberated from γδ T-cell regulation. The importance of the environment, which tightly regulates the number of proliferated mast cells, may also be supported by the observation that the number of mast cells in the same size area in NOG mouse skin was almost identical regardless of the origin of the proliferated mast cells.

RT-PCR analysis revealed that murine SCF made a major contribution to human mast cell development in NOG mice. Because we did not administer any human cytokines, the development of human mast cells in NOG mice indicates that SCF alone may be sufficient for human MC T development. It is also possible that some factors produced from human cells developed in mice from transplanted HSCs are synergistically involved with SCF, because human blood cells, including T cells, were reconstituted in NOG mice. Yet another possibility is that recipient mice supply some factors favorable to human mast cell development, which seems to be supported by the previous finding of an increase of human chymase+ dermal mast cells after healthy human skin plantation onto SCID mice.44

In the spleen of NOG mice, we unexpectedly identified abundant human chymase+ mast cell development, indicating that mouse spleen may provide a suitable condition for the development of human connective-tissue-type mast cells from the HSCs or committed precursors. A detailed analysis of the molecular-based mechanisms of the environment provided in the spleen should be very helpful for a better understanding of the requirement for human connective-tissue-type mast cell development.

The development of MMCs in NOG mice is of potential interest, because T-cell–derived cytokines are reportedly important for murine MMC development. Although NOG mice lack murine T cells, we found safranin-negative, Alcian blue+ murine MMCs at almost normal concentrations in gastric mucosa, suggesting that factors supporting murine MMC development are produced not only by T cells.45 Similarly, the factors required for human MC T development remain unclear. Although some factors produced by reconstituted human T cells or other human progenies may support MC T development in NOG mice, another possibility is that SCF is sufficient for mucosal-type mast cell development in humans. In mice, parasite infection induces reactive MMC proliferation depending on the action of IL-3,46,47 so that parasite infection of NOG mice which have undergone xenotransplantation may provide more information about human MC T development.

The absence of phenotypically identified mast cells on the smear preparations and CD203c/Kit double-positive cells analyzed by flow cytometry in peripheral blood indicates that human mast cells develop from immature cells without a characteristic phenotype and that their complete differentiation into mature mast cells takes place only after they have migrated to peripheral tissues. This hypothesis seems to be supported by cluster formation of human mast cells in NOG mice. Human mast cell development from contaminated precursors is unlikely, because the time course of human mast cell appearance in NOG mice that received transplants of lin−/CD34+ cells was not different from mice that received transplants of whole CD34+ cells. Whether immature cells circulating in the peripheral blood are either already committed to becoming mast cells or maintain their capability to differentiate into other lineages than mast cells is an interesting subject for further studies.

In this study, we established for the first time an in vivo model for human mast cell development. Not only human connective tissue-type MC T but also human mucosal-type MC T can develop in NOG mice. Our model, thus, provides useful information about human mast cell development from HSCs in vivo. In addition, this model may also pave the way to a potential tool for the in vivo investigation of human mast cell functions.

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References


Figure 8. Immunochemical staining for human mast cell-specific chymase in mesentery, lymph nodes, and spleen. (A) In the mesentry, human mast cells formed clusters consisting of 2 to 6 chymase+ cells. (B) In the lymph nodes, chymase+ cells localized around vessels in the trabecula. (C-D) Abundant chymase+ cells were extensively distributed in the red pulp but not in the white pulp of the spleen. Magnification, × 400 (A,B,D) and × 100 (C).
HUMAN MAST CELL DEVELOPMENT IN MICE


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Development of both human connective tissue-type and mucosal-type mast cells in mice from hematopoietic stem cells with identical distribution pattern to human body

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