Heterogeneity Among Ly-49C Natural Killer (NK) Cells: Characterization of Highly Related Receptors with Differing Functions and Expression Patterns

By Jack Brennan,*‡ Suzanne Lemieux,§ J. Douglas Freeman,* Dixie L. Mager,*‡ and Fumio Takei*†

From the *Terry Fox Laboratory, British Columbia Cancer Agency; the ‡Department of Medical Genetics, and the §Department of Pathology and Laboratory Medicine, the University of British Columbia, Vancouver, British Columbia; and the †Centre de Recherche en Immunologie, Institut Armand-Frappier, Université du Québec, Laval, Québec, Canada

Summary

Ly-49C is a member of the polymorphic family of murine NK cell inhibitory receptors. The 5E6 antibody that defines a subset of NK cells responsible for the rejection of parental H-2d bone marrow by F1 mice has been shown previously to react with Ly-49C. Here, the 5E6 antibody was found to detect two Ly-49C-related molecules in B6 mice. Two cDNA clones were isolated from B6 NK cells, one identical to previously reported Ly-49C B6 and the other a novel cDNA. The deduced amino acid sequence of the latter differs from that of Ly-49C BALB at only 4 residues, whereas the previously reported Ly-49C B6 differs at 22 residues. Flow cytometric analyses of COS cells transfected with the two cDNAs showed that the 5E6 antibody binds to both Ly-49 molecules, while another anti-Ly-49C antibody, 4LO3311, binds to the newly described Ly-49C but not the previously reported Ly-49C B6. Two-color flow cytometric analysis detected 5E614LO3311 subsets of NK cells from B6, but not BALB/c, mice. The level of Ly-49C expression on B6 NK cells detected by the 4LO3311 antibody was substantially lower than that on BALB/c NK cells. Binding specificity of the novel Ly-49C B6 was indistinguishable from that of Ly-49C BALB, whereas no binding was detectable with previously reported Ly-49C B6. These results demonstrate that the newly described Ly-49C B6, not the previously reported Ly-49C B6, is the probable B6 allelic form of Ly-49C. The previously reported Ly-49C B6 must be encoded by a separate gene and should be renamed Ly-49I. The implication of these results with respect to the role of Ly-49C in hybrid resistance is discussed.

Ly-49C is a member of the Ly-49 family of NK cell inhibitory receptors (1). It was initially identified through gene cloning based on cross-hybridization with the Ly-49A probe (2). The 5E6 antibody, which detects NK subsets responsible for hybrid resistance against H-2d but not H-2b bone marrow grafts in F1 hybrid mice (3), was subsequently found to bind to Ly-49C (4). Flow cytometric analysis of NK cells showed that Ly-49C is expressed in distinct NK subsets (4, 5). In in vitro cytotoxicity assays, 5E6+ NK cells from (NZB × B6)F1 mice lyse BALB/c (H-2b) but not B6 (H-2b) target cells (5). The resistance of H-2b target cells to 5E6+ F1 NK cells is reversed by the 5E6 antibody. Therefore, Ly-49C is considered to be an inhibitory NK receptor for class I MHC. The specific interaction between Ly-49C and class I MHC has been demonstrated by the binding of cells to Ly-49C-transfected COS cells and inhibition of the cell binding by specific class I MHC antibodies (4, 6).

Further studies to elucidate the functional role of Ly-49 in the regulation of NK cytotoxicity are complicated by the fact that Ly-49 represents a closely related and highly polymorphic family of molecules. It is currently difficult to determine whether Ly-49 molecules in different strains of mice represent allelic forms of the same loci or whether they are encoded by different genes. Furthermore, allelic forms of Ly-49 molecules may differ from each other in their specificities for class I MHC. These problems are particularly relevant to hybrid resistance. The initial Ly-49C cDNA to be described was isolated from a (B6 × CBA)F1 mouse cDNA library (2). The identical gene was found to be expressed in BALB/c mice. A related gene, isolated from B6 mice, differs from Ly-49C BALB in 22 amino acid residues but has been considered to be the allelic form (7). Both Ly-49C BALB and Ly-49C B6 are detected by the 5E6 antibody. In in vitro cytotoxicity assays, 5E6+ NK cells
from B6 mice are able to kill H-2d, but not H-2b, target cells, while those from BALB/c mice kill neither H-2d nor H-2b targets (5). This difference is thought to be due to different ligand specificities of the two putatively allelic forms of Ly-49C. It is unknown why 5E6+ NK cells of F1 mice that express either or both of the two allelic forms of Ly-49C fail to receive negative signals from parental H-2d bone marrow cells.

In this study, we further characterize Ly-49C from B6 and BALB/c mice by cDNA cloning as well as with a newly available Ly-49 antibody. Our results demonstrate that the 5E6 antibody that has been used to identify Ly-49C in fact recognizes two distinct Ly-49C-related receptors in B6 mice and that the two receptors are differentially expressed on B6 NK cell subsets. One of the two B6 Ly-49 molecules identical to previously reported B6 Ly-49C shows no specific binding to H-2d or H-2b targets, whereas the second B6 Ly-49C molecule binds to class I MHC in a manner indistinguishable from the BALB/c receptor. Based upon sequence homology, the latter receptor is most likely the B6 allele Ly-49C, whereas the former must be the product of another gene highly related to Ly-49C. Therefore, these findings call for a reevaluation of previous studies that have equated 5E6+ NK cells with Ly-49C, particularly with regard to the role of the Ly-49C receptor in hybrid resistance (5), as well as its potential allelic exclusion (7, 8).

Materials and Methods

Antibodies and Flow Cytometry. The 4LO3311 antibody has been described (9). The 5E6 hybridoma was provided by Dr. V. Kumar (University of Texas Southwestern Medical Center, Dallas, TX). Flow cytometric analysis of transfected COS were carried out as described (4). NK cell staining procedures were as follows: splenic NK cells (3–5 × 106) were first incubated with unlabeled anti-FcR Ab to block nonspecific binding of anti-Ly-49C antibodies. This Ab was purified from the supernatant of unlabeled anti-FcR Ab to block nonspecific binding of anti-Ly-49C hybridoma line purchased from the American Type Culture Collection (Rockville, MD). NK cells were then stained with FITC-conjugated 5E6, biotinylated 4LO3311, or both Ab

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Ly-49C PCR. PCR primers specific for Ly-49C were designed corresponding to sequences located in the 5’ and 3’ untranslated regions of the Ly-49C-BALB transcript. The sequences of the oligonucleotides were 5’-AGTACCGCGGAACGCCA-CTTTCA-3’ and 5’-TACTCCCGGGAGACTATGTCTGTGAA-3’. The first strand of cDNA was generated in a 25 µl mixture containing 10 µg total RNA (isolated from B6 NK cells cultured for 10 d in 1,000 U of IL-2), 0.5 mM each of four deoxynucleotidetriphosphate (triphasphate), 4 µg/ml random hexamers, 10 mM diithiothreitol, and 200 U of reverse transcriptase. The reaction was incubated at 37°C for 1 h followed by 5 min at 95°C to inactivate the enzyme. 1 µl of this reaction was then subjected to PCR using Elongase (Canadian Life Technologies, Burlington, Ontario) according to the protocols provided by the manufacturer. 35 cycles were carried out as follows: 1 min denaturation at 94°C, 1 min annealing at 45°C; and 3 min extension at 72°C. This was followed by a final extension for 5 min at 72°C. PCR products of ~1 kb in size were purified from a 0.8% agarose gel, cut with SstII to remove the primer tails, and subcloned into the SstII site of pBluescript-KS+. All PCR-derived clones described in this paper were obtained in at least two independent PCR and subcloning experiments and were sequenced in their entirety.

Transfections and Adhesion Assays. The Ly-49A-BALB cDNA was isolated by PCR as described by Held et al. (8). The Ly-49E-BALB and Ly-49F-BALB cDNAs (11) were obtained from Dr. W. Yokoyama (Washington University, St. Louis, MO), and the Ly-49G-BALB cDNA was provided by Dr. S. Anderson (NCI, Frederick, MD). Transfection of COS cells with Ly-49 cDNA and cell adhesion to the transfected COS cells were carried out as described (4).

Results

Isolation of Ly-49C cDNAs from BALB/c and C57BL/6 Mice. Southern blot analysis of genomic DNA of B6 mice using a single exon probe derived from the 3’ end of the Ly-49C cDNA revealed 4–5 hybridizing bands (data not shown). Under the conditions used, the probe cross-hybridized with Ly-49H cDNA but not other Ly-49 cDNAs
identified thus far (Ly-49 A, B, D, E, F, and G). Each band likely represents an individual gene (or possibly pseudogenes), because sites for the restriction enzymes used for the analysis are not found within the single exon probe. To identify Ly-49C-related genes in B6 mice, PCR was performed on cDNA prepared from IL-2-activated NK cells from B6 mice. The PCR primers used in these experiments were designed so as to amplify Ly-49C and none of the other known members of the Ly-49 family. A total of eight clones were generated and fully sequenced. One of them was found to be identical to Ly-49CBALB previously reported (7), and the other seven all encoded a novel cDNA highly related to Ly-49CBALB. The predicted protein encoded by the novel B6 cDNA differs from the Ly-49CBALB by only 4 amino acids, whereas the previously reported Ly-49CB6 differs at 22 amino acid residues (Fig. 1). At the nucleotide level, the coding region of the novel cDNA is 99.3% identical to that of BALB/c Ly-49C cDNA, whereas the previously reported cDNA sequence is 95.9% identical to the BALB/c form. For clarity, the previously reported Ly-49CB6 has been renamed Ly-49CB6 and the newly described cDNA designated Ly-49CB6.

**Specificities of Anti-Ly-49C Antibodies.** The 4LO3311 antibody was previously reported to detect the NK cell antigen NK2.1 (9, 12). The specificity of this antibody for Ly-49 was tested by the binding to COS cells transfected with individual Ly-49 cDNAs. Flow cytometric analysis of the transfected COS cells showed that 4LO3311, like 5E6, recognizes Ly-49CBALB but not Ly-49A_BALB, Ly-49A_BALB, B_BALB, D_BALB, E_BALB, F_BALB, G_BALB, or H (Gosselin, P., Y. Lusignan, J. Brennan, F. Takei, D. Mager, and S. Lemieux, manuscript submitted for publication). When the two B6 Ly-49C-related molecules were tested, 4LO3311 bound only to the novel Ly-49CB6, while 5E6 reacted with both B6 Ly-49C and Ly-49I (previously reported Ly-49CB6) (Fig. 2A). Therefore, according to this serologic reactivity, Ly-49CBALB and Ly-49CB6 are 5E6+4LO3311+, and Ly-49IB6 is 5E6+4LO3311-.

As a tool to identify the domains recognized by the 4LO3311 antibody, chimeric Ly-49CBALB/Ly-49CB6 cDNA constructs (6) were expressed in COS cells and tested for their antibody reactivity. 5E6 has previously been found to bind epitopes contained within the carbohydrate recognition domain (CRD)1 (6). However, 4LO3311, was shown to recognize an epitope located in a 32-amino acid segment of the stalk region immediately adjacent to the CRD (Fig. 2B). This region has previously been shown to be important for specific binding of Ly-49C to class I MHC. In light of the 4 amino acid differences between Ly-49CBALB and Ly-49IB6 in this region (see Fig. 1), combined with 4LO3311 reactivity with the former but not the latter, it follows that one or more of these four amino acid residues contribute to the epitope recognized by 4LO3311. It is also possible that the lack of an NH2-linked glycosylation site in this region of Ly-49IB6 affects the binding of the 4LO3311 antibody.

**Ly-49C+ NK Cell Subsets.** The expression of Ly-49C on NK cells from BALB/c and B6 mice was examined by flow cytometry using the 5E6 and 4LO3311 antibodies. The 4LO3311 antibody stained significant fractions of NK cells from B6 as well as BALB/c mice (Fig. 3A), but there were significant differences between BALB/c and B6 NK cells. The staining of BALB/c NK cells with the 4LO3311 antibody was 10-fold more intense than that of B6 NK cells, and two times more positive cells were detected in BALB/c mice.

Two-color analysis of NK-enriched spleen cells showed that BALB/c mice possess only NK cells that are either double-positive or double-negative for the 5E6 and 4LO3311 antibodies. In contrast, the B6 NK population consists of double negative, double positive, and single positive (5E6+ 4LO3311-) subsets (Fig. 3B). Based on the specificities of the 5E6 and 4LO3311 antibodies described above, these flow cytometric analyses indicate that the two B6 Ly-49C-related molecules are expressed on distinct but possibly

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1. **Abbreviation used in this paper:** CRD, carbohydrate recognition domain.
overlapping subsets of NK cells, while no such heterogeneity is observed with BALB/c NK cells. It should be noted that the double-positive subset of B6 NK cells seems to contain at least two populations differing in the intensities of 5E6, but not 4LO3311, staining. They may represent cells expressing Ly-49C alone and those coexpressing Ly-49C and Ly-49I. It is also possible that these two antibodies may detect other Ly-49 molecules yet to be described on the double positive population.

Recognition of Class I MHC by B6 and BALB/c Ly-49C Receptors. 5E6+ NK cells have been thought to receive negative signals upon interactions of Ly-49C with H-2^b and, under certain circumstances, H-2^d antigens on target cells. After having shown that 5E6+ NK cells in B6 mice actually comprise two distinct NK cell subsets and that each of these express distinct but highly related receptors, we next investigated the class I MHC binding properties of each of these B6 receptors. It has been shown previously that Ly-49A_B6 and Ly-49C_BALB expressed on COS cells by cDNA transfection mediate cell–cell adhesion by binding to class I MHC antigens on various opposing cell lines (6). Ly-49A_B6 has been shown to bind H-2^d structures (but not H-2^b), whereas Ly-49C_BALB binds to both H-2^d and H-2^b.

When this same assay was used to test the B6 Ly-49 receptors, Ly-49C_B6 bound to both H-2^d and H-2^b, as was the case for the highly related Ly-49C_BALB (Fig. 4 A). Interestingly, Ly-49I_B6 did not show any class I binding ability in this assay system. The binding was almost completely inhibited by the 4LO3311 antibody (Fig. 4 B), further indicating that the cell adhesion in this system is mediated by Ly-49C.

Discussion

The results presented in this report have demonstrated that two Ly-49C-related molecules are expressed on NK cells from B6 mice. Although Ly-49C^+ NK cells in B6 mice were previously identified by the 5E6 antibody, our current data have shown that this NK subset is, in fact, heterogeneous and can be divided into subpopulations based on the expression of the two Ly-49 molecules. One of the two Ly-49 molecules described in this study, Ly-49I_B6, is identical to the previously reported Ly-49C_B6 that was considered to be allelic to Ly-49C_BALB (7). However, the deduced amino acid sequence of the other Ly-49C is much closer to...
the Ly-49\textsuperscript{CB\textsubscript{BALB}} sequence than that of Ly-49\textsuperscript{I} (4 residue difference versus 22 residue difference). More importantly, this newly described Ly-49\textsuperscript{CB\textsubscript{B6}} shows the same binding specificity for class I MHC as that of Ly-49\textsuperscript{CB\textsubscript{BALB}}, whereas no binding of Ly-49\textsuperscript{I} to those class I MHC is detectable in the cell binding assays in this study. Therefore, the newly described Ly-49\textsuperscript{CB\textsubscript{B6}} is more likely the B6 allelic form of Ly-49\textsuperscript{C}. The previously reported Ly-49\textsuperscript{CB\textsubscript{B}} must be encoded by a different but highly related gene and has been renamed Ly-49\textsuperscript{I\textsubscript{B6}}.

Based on our finding that the 5E6 antibody binds to two different Ly-49 receptors, Ly-49\textsuperscript{CB\textsubscript{BALB}} and Ly-49\textsuperscript{CB\textsubscript{B6}}, on B6 NK cells and that these receptors differ in terms of their class I recognition abilities and expression on NK cell subsets, our previous understanding of 5E6\textsuperscript{+} NK cells is considered both simplistic and inaccurate. The 5E6 antigen was originally defined as a marker of an NK cell subset in F\textsubscript{1} hybrid mice that rejects parental H-2\textsuperscript{d} but not H-2\textsuperscript{b} bone marrow grafts (3). The subsequent identification of 5E6 as Ly-49\textsuperscript{C} and the modulation of NK cell killing in vitro with anti-5E6-Ab has served as strong support that this molecule functions as an inhibitory receptor for class I MHC (5). Consequently, inhibition of NK cytotoxicity by Ly-49 is dependent on its level of expression, which is controlled by the affinity of interaction between Ly-49 and particular self-MHC. We have demonstrated that the level of Ly-49C on BALB/c NK cells is nearly 10-fold higher than the level of Ly-49\textsuperscript{CB\textsubscript{B6}} on B6 NK cells as determined by the staining with the 4LO3311 antibody (Fig. 3A). Based on the receptor calibration model, it is likely that the affinity of the interaction between Ly-49C and H-2\textsuperscript{d} is lower than that between Ly-49C and H-2\textsuperscript{b}. Thus, Ly-49\textsuperscript{C\textsubscript{BALB}} is more likely to be preferentially expressed on 5E6\textsuperscript{+} NK cells because of the high level of Ly-49C expression. In contrast, Ly-49\textsuperscript{C\textsubscript{B6}} NK cells from B6 mice, and likely from F\textsubscript{1} mice as well, fail to receive inhibitory signals from H-2\textsuperscript{d} target cells due to its relatively high affinities for class I MHC. However, our present results indicate that Ly-49\textsuperscript{CB\textsubscript{BALB}} and the likely B6 allelic form, Ly-49\textsuperscript{CB\textsubscript{B6}}, have the same binding specificities, whereas Ly-49\textsuperscript{I\textsubscript{B6}} does not bind to H-2\textsuperscript{d} or H-2\textsuperscript{b} target cells.
finity interaction. Recent findings that the expression level of Ly–49C is indeed regulated by class I MHC of the host (Gosselin, P., Y. Lusignan, J. Brennan, F. Takei, D. Mager, and S. Lemieux, manuscript submitted for publication) further supports this model.

It is of interest that the 4LO3311 antibody binds to the stalk region of Ly–49C and yet it effectively inhibits the binding of target cells to Ly–49C-transfected COS cells. On the other hand, 5E6 binds to the CRD and also inhibits the binding of class I MHC to Ly–49C. Previous studies of Ly–49C have found sequences in both the CRD and in the stalk region immediately adjacent to the CRD to be important in binding to class I MHC (6). The results with 4LO3311 further support the hypothesis that the recognition of class I MHC involves both the CRD and the stalk region of Ly–49C.

These results have demonstrated the complexity of the NK cell receptor Ly–49. The unexpected cross-reactivity of the 5E6 antibody exemplifies the potential problem associated with a highly polymorphic and complex family of molecules such as Ly–49. Until all the Ly–49 genes and the proteins are identified, precise specificities of existing Ly–49 antibodies require careful examination. At the same time, our results suggest a relatively simple explanation of the question of how hybrid resistance is regulated by Ly–49. The finding that the previously reported Ly–49C<sup>B6</sup> is unlikely to be the B6 allelic form of Ly–49C also calls for a re-evaluation of allelic exclusion of Ly–49C (8).

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Address correspondence to Fumio Takei, Terry Fox Laboratory, British Columbia Cancer Agency, 601 West 10th Avenue, Vancouver, British Columbia, V5Z 1L3 Canada.

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