Functional Dichotomy in Natural Killer Cell Signaling: Vav1–Dependent and –Independent Mechanisms

By Francesco Colucci,* Eleftheria Rosmaraki,* Søren Bregenholt,* Sandrine I. Samson,* Vincenzo Di Bartolo,‡ Martin Turner,§ Lesley Vanes,‖ Victor Tybulewicz,‖ and James P. Di Santo*

From the *Laboratory for Cytokines and Lymphoid Development and the ‡Laboratory for Molecular Immunology, Pasteur Institute, 75015 Paris, France; §The Babraham Institute, Cambridge CB2 4AT, United Kingdom; and ‖The National Institute for Medical Research, London NW7 1AA, United Kingdom

Abstract

The product of the protooncogene *Vav1* participates in multiple signaling pathways and is a critical regulator of antigen–receptor signaling in B and T lymphocytes, but its role during in vivo natural killer (NK) cell differentiation is not known. Here we have studied NK cell development in $Vav1^{-/-}$ mice and found that, in contrast to T and NK-T cells, the absolute numbers of phenotypically mature NK cells were not reduced. $Vav1^{-/-}$ mice produced normal amounts of interferon (IFN)-γ in response to *Listeria monocytogenes* and controlled early infection but showed reduced tumor clearance in vivo. In vitro stimulation of surface receptors in $Vav1^{-/-}$ NK cells resulted in normal IFN-γ production but reduced tumor cell lysis. Vav1 was found to control activation of extracellular signal-regulated kinases and exocytosis of cytotoxic granules. In contrast, conjugate formation appeared to be only mildly affected, and calcium mobilization was normal in $Vav1^{-/-}$ NK cells. These results highlight fundamental differences between proximal signaling events in T and NK cells and suggest a functional dichotomy for Vav1 in NK cells: a role in cytotoxicity but not for IFN-γ production.

Key words: tumor clearance • *Listeria* infection • exocytosis • lymphoid development • cytokines

Introduction

The protooncogene *Vav1* is one of three members of the Vav family of guanine nucleotide exchange factors (GEFs)[1] for the small GTPases of the Rho family (1). Its product, p95^vav1 (or Vav1) contains an array of structural motifs including a Dbl homology domain, a single Src homology (SH)2 and two SH3 domains, a pleckstrin homology domain, and a calponin homology domain, enabling it to interact with different proteins involved in multiple signal transduction pathways (1). Vav1 is expressed preferentially in hematopoietic cells (2) and is rapidly phosphorylated after stimulation of growth factor receptors and Ag receptors on B and T lymphocytes (3–5). Upon tyrosine phosphory-

lation, Vav1 promotes Rac1 and other Rho family proteins to their active GTP-bound state (6–10), thereby mediating vital functions such as survival, differentiation, motility, and cell division (1, 11). In lymphocytes, activation of the small Rho family proteins by Vav1 promotes Ag–receptor capping, actin polymerization, and Ag-induced proliferation of B and T cells in vitro and effective T cell selection in vivo (5, 12–17). Therefore, it is clear that Vav1 is essential for T cell development and for Ag–receptor-induced responses of B and T lymphocytes. In contrast, signaling requirements for NK cell development are not fully appreciated, although soluble growth factors (including Flt3L/Flk2L, stem cell factor [SCF], IL-7, and IL-15, which appear to be the dominant cytokines) and stromal elements in the bone marrow are essential (18–22). Because Vav1 has been reported to be part of the signaling pathways activated by the receptors for Flt3L/Flk2L and SCF (23, 24), it may be crucial in early NK cell development.

Vav1 may participate in signaling pathways during the activation of NK cells. Proximal events, including phosphorylation of phosphatidylinositol 3 kinase (PI3K) and phos-

Address correspondence to Francesco Colucci, Laboratory for Cytokines and Lymphoid Development, Department of Immunology, The Pasteur Institute, 25 rue Dr. Roux, 75015 Paris France. Phone: 33-1-4061-3664; Fax: 33-1-4061-3510; E-mail: cecco@pasteur.fr

    [1]*Abbreviations used in this paper:* ADCC, antibody-dependent cell cytotoxicity; ERK, extracellular signal-regulated kinase; GEFs, guanine nucleotide exchange factors; *L.m.*, *Listeria monocytogenes*; MAPK, mitogen-activated protein kinase; PI3K, phosphatidylinositol 3 kinase; PLC, phospholipase C.

pholipase C (PLC), participate to sustain the rise in intracellular calcium, a necessary second messenger during NK cell effector functions (25). In T cells, Vav1 is a critical transducer of TCR signals to the calcium pathway, and in its absence, T cells fail to initiate IL-2 gene transcription and proliferate (26). Vav1 has the ability to bind and be regulated by the lipid substrates and products of PI3K (27). Vav1 has also been proposed to enhance the production of substrates for PLCγ2 through activation of phosphatidylinositol 4-phosphate 5 kinase (28). In line with this, the PI3K-specific inhibitor wortmannin abolishes antibody-dependent cell cytotoxicity (ADCC; reference 29), and mice deficient for PLCγ1 have decreased natural cytotoxicity (30).

Vav1 is phosphorylated upon contact with tumor targets and upon cross-linking of the sole FcR (FcγRII/III, CD16) expressed by NK cells (31, 32) and therefore may be required for NK cell functions. Virally infected cells produce IFN-α/β, which are potent activators of NK cells and have been shown to induce phosphorylation of Vav1 in several hematopoietic lineages, including lymphocytes (33).

Binding of NK cells to tumor cells and stimulation of NK cells via CD16 results in activation of the mitogen-activated protein kinase (MAPK) cascades. One of this cascades, the extracellular signal-regulated kinase (ERK) is part of the intracellular signaling leading to IFN-γ production, granule exocytosis, and cytotoxicity by NK cells (34–36). In T cells, Vav1 is required to transduce TCR signals to the ERK pathway (26), thereby mediating gene transcription. By analogy, Vav1 may be involved in the process of IFN-γ production in NK cells. On the other hand, p38 MAPK is also activated upon binding of NK cells to tumor targets and leads to cytokine production and cytotoxicity (37). However, Vav1 does not seem to be an essential regulator either of the p38 MAPKs or of the c-Jun NH$_2$-terminal kinase (JNK, or stress-activated kinase, SAPK) in T cells (15, 16, 26).

Inactivation of the Vav1/Rac1 pathway in human NK cell lines has helped address the role of Vav1 in NK cell functions. As such, Vav1 has been shown to be critical for signaling through CD16 and through the receptor(s) mediating natural cytotoxicity (32, 38). In these studies, it was reported that natural cytotoxicity and ADCC were both decreased in human NK cell lines in the presence of a dominant-negative form of Rac1 (32), or antisense oligonucleotides for Vav1 (38). However, whether deficiency in Vav1 will affect NK cell ontogeny or cytokine production has not yet been investigated. Here, we characterize NK cell differentiation in Vav1$^{-/-}$ mice.

Materials and Methods

Mice. Vav1$^{-/-}$ mice on the B10.BR background were derived as described (14). Vav1$^{-/-}$, B10.BR (*wt*), Rag2/γc$^{-/-}$ (39), and Rag2$^{-/-}$ mice (40) were housed at the animal facility of the Pasteur Institute.

FACS® Analysis and Cell Sorting. Cell suspensions were prepared from spleen, thymus, liver, and bone marrow. They were depleted of red cells and stained for flow cytometry as described

(39). mAbs directly conjugated to FITC, PE, Tricolor (TRI), allophycocyanin, or biotin included mAbs specific for CD3, CD4, CD8, CD11a (LFA-1), CD11b (Mac-1), CD19, CD45R (B220), CD90 (Thy-1.2), CD117 (c-kit), CD122 (IL-2Rβ), CD161 (NK1.1), DX5, 2B4, Ly49A, Ly49C/I, Ly49D, Ly49G2, TCR-α/β, IgM (all from PharMingen), and H-2K^k (Caltag Laboratories). Biotin–conjugated mAbs were revealed by streptavidin–TRI (Caltag). Cells (10^6) were first incubated with anti–FcγRII/III (hybridoma 2.4G2) for 20 min on ice to avoid unspecific binding to low-affinity FcRs. To purify cells, splenocyte suspensions were stained with mAbs specific for NK1.1–PE and CD3–FITC: CD3$^-$NK1.1$^+$ NK cells and CD3$^+$NK1.1$^-$ T cells were sorted using a FACStar™ (Becton Dickinson). The purity of the sorted populations was reproducibly >95%. Alternatively, splenocytes were passed over nylon wool columns to deplete myeloid and B cells and thereafter depleted of T cells by panning on anti–TCR-β (clone H57) coated Optilux® Petri dishes (Falcon). Cells were then expanded in IL-2 (1,000 U/ml) for 7–10 d.

In Vivo NK Cell Functions. A standard lung clearance assay was used to test the ability of mice to reject tumors in vivo as described (41). Briefly, RMA-S cells (10^6) were labeled in 100 μCi of ^{51}Cr for 1 h at 37°C, and after several washings, 10^5 cells per mouse were injected intravenously. 4 h later, mice were killed, and the residual radioactivity was measured in the explanted lungs. In a typical experiment, total radioactivity of the injected inoculum (10^5 cells/200 μl) would be ∼25–50,000 cpm. In a second tumor model, modified from that described in reference 43, RMA-S cells (2.5 × 10^5) were injected intraperitoneally, and 48 h later the peritoneal exudate cells recovered, counted, and stained with mAbs specific for CD3, NK1.1, and H-2K^k. Residual tumor cells could readily be distinguished by their larger size, CD3 staining, and absence of H-2K^k staining. In the lymphoma metastases model, mice were injected intravenously with H-2–compatible (H-2^k) but class I^{low} RDM4 cells (10^4), and survival was scored for up to 14 d. Those mice that survived were killed at day 14 and their livers fixed in Bouin's medium for 48 h. Macroscopic metastases were readily detected by visual inspection. For the infection model, 10^4 *Listeria monocytogenes* (*L.m.*) bacteria (strain LO28) were injected intravenously, and 48 h later the serum was collected from each mouse and the IFN-γ content was quantified by ELISA (Genzyme). Bacterial burden in livers and spleens was determined 48 h after injection as described previously (42).

In Vitro NK Cell Cytotoxicity. A standard ^{51}Cr-release assay was used to measure NK activity in vitro as described (43). Target cells (H-2^a murine YAC-1 thymoma, H-2^b murine macrophage tumor line IC-21, H-2^b murine EL-4 thymoma, H-2^d murine P815 mastocytoma, Con A–activated B10.BR and β2m$^{-/-}$ blasts, and H-2^b murine lymphomas RMA and transporter associated with antigen processing [TAP]-deficient RMA-S) were labeled with 100 μCi ^{51}Cr (ICN Pharmaceuticals), and 2.5–5 × 10^3 targets were incubated with graded numbers of effector cells in 200 μl of medium for 4 h. For natural cytotoxicity, effector cells were NK-enriched splenocytes (by passage on nylon wool columns) from untreated mice or from mice primed 40 h earlier with 0.2 mg of poly(I:C) (Sigma-Aldrich). NK-enriched splenocytes and FACS®-purified NK cells were expanded in IL-2 (1,000 U/ml) for 7–10 d and thereafter used as effectors for (a) ADCC using EL-4 cells coated with anti–Thy-1.1 mAb (lysis of EL4 cells without the Ab never exceeded 10% at the highest E/T ratios); (b) "reverse" ADCC (R-ADCC) using FcR$^+$ P815 cells in presence or absence of anti-NK1.1, anti-2B4, or anti-CD16 mAbs; (c) MHC inhibition and recognition of "missing self" using Con A–activated B10.BR and β2m$^{-/-}$ blasts or RMA and

RMA-S cells. MHC class I⁺ Con A blasts (*wt*) or MHC class I⁺ RMA cells were both resistant to lysis (<5%), even at the highest E/T ratios. Radioactivity released into the cell-free supernatant was measured, and the percent specific lysis was calculated as following: $100 \times$ (experimental release − spontaneous release)/ (maximum release − spontaneous release).

In Vitro Cytokine Production. Sorted NK cells (2×10^4 cells/ 200 μl) were cultured in flat-bottomed microtiter plates in human IL-2 (1,000 U/ml) and stimulated with murine IL-12 (2 ng/ ml; PeproTech) or mAbs specific for NK1.1 (clone PK136, 20 μg/ml), 2B4 (5 μg/ml), CD16 (75 μg/ml), or control anti–Gr-1 mAb (10 μg/ml). Wells were precoated with mAbs (50 μl/well) for 4 h before adding NK cells. After 24 h, the cell-free supernatants were collected and the amount of IFN-γ was quantitated by ELISA (Genzyme). In parallel experiments, FACS®-purified NK and T cells (2×10^5) were incubated in the presence of brefeldin A (10 μg/ml) for 4 h at 37°C on flat-bottomed microtiter plates precoated with anti-NK1.1 or anti-CD3. Cells were then washed, fixed in 2% paraformaldehyde for 30 min on ice, thereafter stained with anti-IFN-γ–FITC (PharMingen) in 0.5% saponin. As controls, cells were incubated in medium alone or with PMA (50 ng/ml) and ionomycin (1 μg/ml).

Conjugate Formation. IL-2–activated NK cells (2×10^5) were labeled with 1 μg/ml of 2′-7′-biscarboxyethyl-5(6)-carboxyfluorescein (BCECF; Calbiochem) for 30 min at room temperature, washed, and mixed with a 1:1 ratio of YAC-1 targets that had been labeled with 40 μg/ml of hydroethydine (HE; Polysciences, Inc.) for 10 min at room temperature. Cell mix was spun at 1,000 rpm for 5 min and incubated for 1, 2, 5, 10, or 20 min at 37°C.

After gentle resuspension, cells were analyzed by flow cytometry. BCECF emits in FL1 and HE emits in FL3, therefore conjugates can be readily detected as double positive (FL1/FL3). Controls were sham conjugates obtained by centrifuging and incubating under the same conditions differentially labeled (HE and BCECF) YAC-1 cells. Background double-positive staining was reproducibly <1%.

Calcium Flux. Purified NK and T cells were labeled with 5 μg/ml of Indo-1 (Molecular Probes) for 45 min at 37°C. Washed cells were resuspended in 10% RPMI and divided into aliquots (5×10^5 cells each) that were incubated for 30 min at 4°C with 20 μg/ml of one of the following mAbs: anti-2B4, anti-NK1.1, anti-CD16, anti-Ly49D, or anti-CD3. Cells were then washed and kept at room temperature until analysis, which was done using an LSR flow cytometer (Becton Dickinson). Immediately before acquisition, cells were resuspended in 500 μl of prewarmed medium. Acquisition was performed for 45 s to set the baseline and then briefly interrupted to add 25 μg/ml of goat F(ab′)₂ anti– mouse IgG to cross-link anti-2B4 and anti-NK1.1 mAbs or goat F(ab′)₂ anti–rat IgG to cross-link anti-CD16, anti-Ly49D, or anti-CD3 mAbs, and finally interrupted after 4–5 min to stimulate cells with 1 μg/ml of ionomycin. Cross-linking Abs failed to generate calcium flux in Indo-1–labeled cells not preincubated with primary mAbs.

ERK Activation. NK and T sorted cells were first expanded in IL-2. Before analysis, cells were starved in IL-2–free medium for 4 h at 37°C and thereafter incubated on ice for 30 min with 20 μg/ml of anti-NK1.1 or anti-CD3 mAbs, followed by cross-linking with the relevant F(ab′)₂ Ab for 3 min at 37°C. As a posi-

A

B
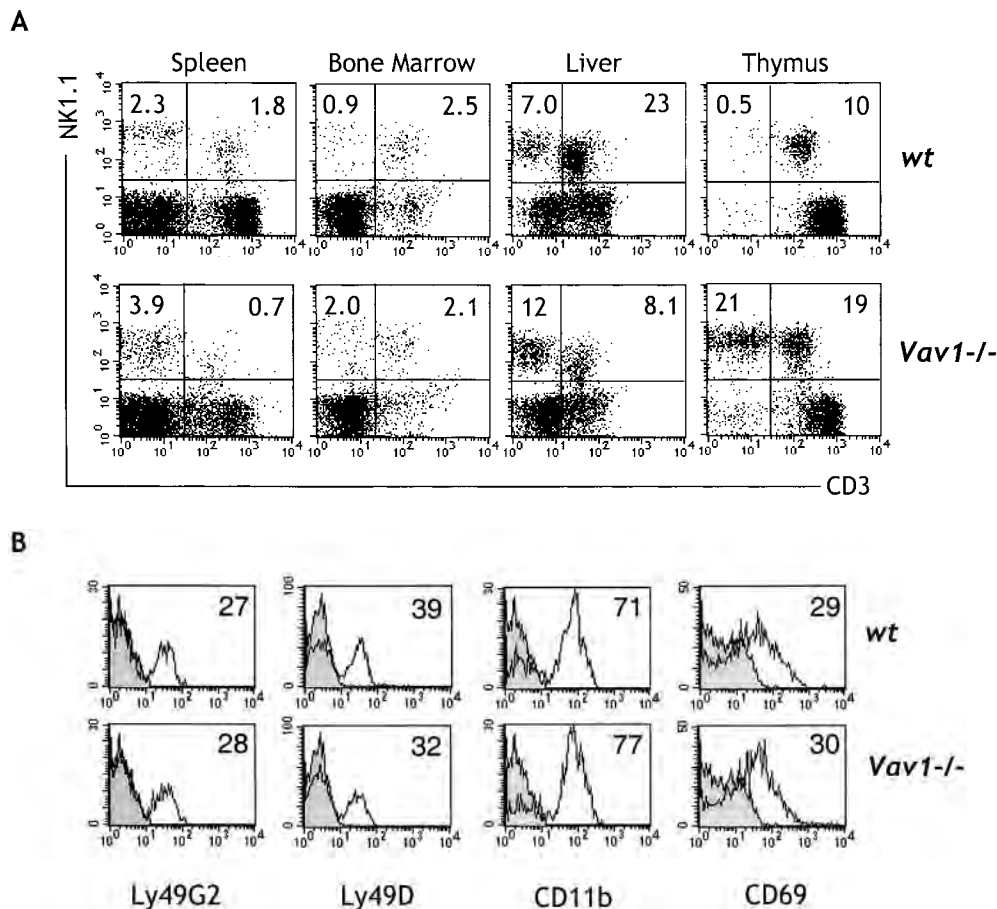
Figure 1. Vav1 is dispensable for NK cell development. (A) Cells from spleen, marrow, and liver were stained with α-CD3^FITC and α-NK1.1^PE mAbs. Thymocytes were stained with α-CD3^FITC, α-NK1.1^PE, and α-HSA^BIO mAb, and a gate was set to exclude HSA⁺ immature cells. Figures in the dot plots indicate percentages of NK, NK-T, and T cells. Data are from one representative of eight independent experiments. (B) Spleen cells were stained with α-NK1.1^PE, α-TCR-αβ^BIO, and α-CD19^BIO and one of the indicated FITC-conjugated mAbs. Biotinylated Abs were revealed with streptavidin–TRI, and only NK1.1⁺ TCR-αβ⁻CD19⁻ NK cells were included in the analysis. Figures show percentage of NK cells staining positive for FITC. No significant differences were detected between *wt* and *Vav1⁻/⁻* NK cells. Results are from one representative of five independent experiments.

tive control, cells were stimulated with 50 ng/ml PMA for 15 min at 37°C. Cells were lysed in 1% NP-40–containing buffer as described (44), and soluble proteins were separated by SDS-PAGE. ERK activation was assessed by immunoblotting with the anti–phospho-ERK mAb E4 (Santa Cruz Biotechnology). The amount of ERK proteins was assessed by reprobing the same membrane with a polyclonal anti-ERK Ab (Santa Cruz Biotechnology). Autoradiographies were quantified by densitometry.

Granule Exocytosis. IL-2–activated NK cells were mixed with YAC-1 cells at a 2:1 ratio. After 4 h, the specific release of esterase was measured in 25 μl of cell-free supernatants after addition of 175 μl of PBS containing 0.22 mM of DNP (Sigma-Aldrich) and 0.2 mM of N-α-benzyloxycarbonyl-L-lysine thiobenzyl ester (BLT; Sigma-Aldrich) as described (44). Maximal release was obtained by measuring the esterase content in the supernatant of NK cells after three freeze–thaw cycles.

Statistics. Statistical significance of data was evaluated by applying Student's *t* test (Microsoft Excel® software).

Results

Vav1 Is Not Required for NK Cell Development but Is Essential for T and NK-T Cell Development. We enumerated lymphocyte subsets in the spleen, bone marrow, liver, and thymus of *Vav1*$^{-/-}$ mice and littermate controls (*Vav1*$^{+/-}$ or *Vav1*$^{+/+}$, hereafter referred to as *wt*). While T and NK-T cells were reduced in *Vav1*$^{-/-}$ mice, NK cell percentages and absolute numbers in the spleen and bone marrow of *Vav1*$^{-/-}$ mice were found to be greater than in controls (Fig. 1 A and Table I). Mature NK cells express a constellation of surface markers, including members of the Ly49 family of MHC receptors, whose upregulation starts at 10 d of age and reaches levels comparable to those of mature NK cells at 2–3 wk of age (45). We found that the expression pattern of 13 different markers on splenic and marrow NK cells (including Ly49A, Ly49C/I, Ly49D, Ly49G2, 2B4, DX5, CD2, CD11b, CD16, CD69, CD90, CD117, and CD122; Fig. 1 B and data not shown) was comparable between *Vav1*$^{-/-}$ and *wt* NK cells. Therefore, Vav1 is not required for NK cell development, unlike T and NK-T cell development.

Vav1 Regulates NK Cell–mediated Tumor Clearance. NK cells recognize cells with disparate class I MHC expression and rapidly kill tumor cells that have lost expression of MHC class I (46). This function can be evaluated in vivo using a short-term assay, where radiolabeled RMA-S (class I–negative) tumor cells are injected intravenously. NK cell antitumor activity is inversely proportional to the radioactivity measured in the lungs. This function is T cell independent, because NK cell–depleted mice cannot reject the injected tumor cells (41). Thus, NK cell–deficient *Rag2/γc*$^{-/-}$ mice retained ∼20% radioactivity, while only ∼1% was found in *wt* mice (Fig. 2 A) or in *Rag2*$^{-/-}$ mice (data not shown). In contrast, *Vav1*$^{-/-}$ mice displayed reduced NK cell activity, as about three- to fourfold more radioactivity was detected (3.4 ± 1% in *Vav1*$^{-/-}$ versus 0.9 ± 0.2% in *wt*; *P* = 0.002).

In a second model of NK cell–dependent tumor rejection (47), we tested the capacity of *Vav1*$^{-/-}$ mice to elimi-

Table I. *Lymphoid Subsets in Vav1*$^{-/-}$ *Mice*

	n	wt	Vav1$^{-/-}$
Spleen			
Total lymphocytes	11	653 ± 140	671 ± 110
NK1.1$^+$CD3$^-$ NK cells	11	**17 ± 5**	**25 ± 7**
NK1.1$^+$CD3$^+$ NK-T cells	8	**9.4 ± 3**	**5.2 ± 2**
TCR-αβ$^+$ T cells	9	**174 ± 19**	**81 ± 22**
IgM$^+$ B cells	10	**415 ± 130**	**533 ± 92**
Bone marrow			
Total lymphocytes	5	23.4 ± 5.4	25.8 ± 6.3
NK1.1$^+$CD3$^-$ NK cells	5	**0.19 ± 0.02**	**0.37 ± 0.17**
Liver			
Total lymphocytes	7	**27.4 ± 9.6**	**10.4 ± 1.7**
NK1.1$^+$CD3$^-$ NK cells	7	1.75 ± 0.5	1.41 ± 0.5
NK1.1$^+$CD3$^+$ NK-T cells	7	**6.2 ± 0.6**	**1.1 ± 1**
Thymus			
Total lymphocytes	9	**587 ± 126**	**100 ± 63**
NK1.1$^+$CD3$^-$ NK cells	9	0.54 ± 0.4	0.8 ± 0.4
NK1.1$^+$CD3$^+$ NK-T cells	9	**5.0 ± 0.24**	**0.42 ± 0.14**

Cell suspensions were enumerated and stained with a mixture of mAbs specific for TCR-αβ, IgM, and NK1.1. Absolute cell numbers were calculated based on the percentages of positive cells out of the total number of lymphoid cells. Statistically significant differences (*P* < 0.05, Student's *t* test) are indicated in bold type. Splenocyte numbers are expressed in 10^6, and for the other organs, cell numbers are expressed in 10^5.

nate intraperitoneally injected RMA-S cells. As shown in Fig. 2 B, 60% of the injected tumor cells were retained in NK cell–deficient *Rag2/γc*$^{-/-}$ mice. In contrast, only ∼0.5% of the inoculated cells were recovered in *wt* mice, while *Vav1*$^{-/-}$ mice retained ∼16-fold more cells (Fig. 2 B), showing a considerable disadvantage in controlling tumor growth. Importantly, the absolute numbers of NK cells in the peritoneal cavity of *wt* and *Vav1*$^{-/-}$ mice were similar, and the injection of tumor cells induced a similar local increase in NK cell numbers (data not shown). Finally, *wt* and *Vav1*$^{-/-}$ mice were injected with H-2–compatible (H-2^K) RDM4 lymphoma cells, which express low levels of class I and therefore should be tolerated by T cells yet sensitive to NK cell lysis. All *wt* mice (four of four) survived for 14 d after the inoculum, and no signs of liver metastases were found at sacrifice (Table II). In contrast, three of five *Rag2/γc*$^{-/-}$ mice succumbed during the 14-d period, and the two surviving mice presented numerous liver metastases. *Vav1*$^{-/-}$ mice showed signs of NK cell deficiency, as one of six mice died, and two of the remaining five mice showed liver metastases at sacrifice. Collectively, these results show that *Vav1*$^{-/-}$ mice have reduced NK cell–mediated antitumor activity in vivo.

Vav1 Is Dispensable for the Early Control of L.m. Infection. NK cells can secrete cytokines (notably IFN-γ, TNF-α, and GM-CSF) during viral or bacterial infections (48). Previous studies suggested that NK cell–derived IFN-γ is critical for early control of infection by *L.m.* (49). There-

A

B

C

D
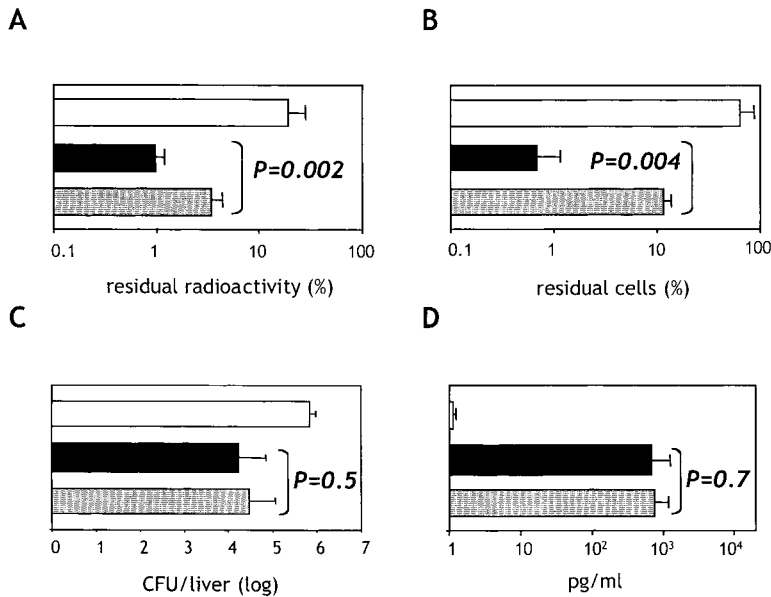
Figure 2. Vav1 is required for antitumor activity but not for antibacterial activity. (A) Mice (five wt, four $Vav1^{-/-}$, three $Rag2/\gamma c^{-/-}$) were injected intravenously with 10^5 ^{51}Cr-labeled RMA-S cells. 4 h after injection, the residual radioactivity was measured in the lungs and is expressed as percentage of the total radioactivity. Data are representative of three separate experiments. (B) Mice (eight wt, five $Vav1^{-/-}$, six $Rag2/\gamma c^{-/-}$) were injected intravenously with 2.5×10^5 labeled RMA-S cells. 48 h after injection, cells in the peritoneal exudate were collected, enumerated, and stained with α-CD3 and α-H-2K^k. Residual RMA-S cells were discriminated by virtue of size and surface phenotype (large CD3$^+$H-2K$^-$ cells). (C) Mice (six wt, six $Vav1^{-/-}$, four $Rag2/\gamma c^{-/-}$) were injected intravenously with 10^4 $L.m.$, and 48 h later liver CFUs were enumerated. (D) The sera from mice infected with $L.m.$ (10 wt, 11 $Vav1^{-/-}$, 4 $Rag2/\gamma c^{-/-}$) were collected after mice were killed, and IFN-γ was detected by standard ELISA technique. P values (Student's t test) are expressed for $Vav1^{-/-}$ versus wt. White bars, $Rag2/\gamma c^{-/-}$; black bars, wt; gray bars, $Vav1^{-/-}$.

fore, we infected $Vav1^{-/-}$ mice and wt mice intravenously with 10^4 $L.m.$, and bacterial burden was measured 48 h later in the liver and spleen (Fig. 2 C). Controls included $Rag2/\gamma c^{-/-}$ and $Rag2^{-/-}$ mice. NK cell–deficient animals displayed an average of ∼10-fold more colonies in liver and spleen (data not shown) as compared with wt mice ($P = 0.002$; Fig. 2 C) or $Rag2^{-/-}$ mice (data not shown). In contrast to the differences found between wt and $Vav1^{-/-}$ mice in tumor clearance, no significant difference was found between wt and $Vav1^{-/-}$ mice in terms of bacterial burden. Thus, $Vav1^{-/-}$ mice can control the early phases of $L.m.$ infection. As IFN-γ appears an essential cytokine for early control of $L.m.$ infection, we measured the IFN-γ levels in the sera of infected mice. Fig. 2 D shows that IFN-γ production by $Vav1^{-/-}$ infected mice was similar to that of wt infected mice. Taken together, these results suggest a functional dichotomy for NK cell functions: normal tumoricidal activity is Vav1 dependent, while IFN-γ production is Vav1 independent.

Vav1 Regulates Natural Cytotoxicity, ADCC, and Lysis Initiated by Distinct NK Cell Receptors but Is Dispensable for IFN-γ Production In Vitro. To dissect the cellular mechanisms responsible for defects in $Vav1^{-/-}$ NK cells in vivo, we compared the lytic activity of freshly isolated and IL-2–activated NK cells from $Vav1^{-/-}$ and wt mice. As shown in Fig. 3, A–E, target cell lysis by $Vav1^{-/-}$ NK cells was defective, ranging from 20 to 50% of control values. The assays included: (a) natural cytotoxicity versus murine thymoma cells (YAC-1), mastocytoma (P815), or macrophage cell line (IC-21); (b) ADCC using EL4 cells precoated with α-CD90; (c) killing of class I–deficient cells (β2m$^{-/-}$ Con A–activated blasts and TAP-deficient RMA-S thymomas); and (d) "reverse" ADCC (R-ADCC) versus FcR$^+$ P815 cells in the presence of α-CD16, α-2B4, or α-NK1.1 mAbs. These results strongly suggest that all forms of NK cell–mediated cytolysis depend on Vav1, irrespective of which cellular receptor is activated. Importantly, prior acti-

vation of NK cells with poly(I:C) in vivo or with IL-2 in vitro did not rescue the lytic defect in $Vav1^{-/-}$ NK cells (Fig. 3, B and D), and no significant difference was observed in the proliferation induced by IL-2 (data not shown).

In contrast, $Vav1^{-/-}$ NK cells responded with normal IFN-γ production (Fig. 4 A), after stimulation of 2B4, CD16, and NK1.1 activating receptors, and with IL-12. It should be noted that stimulation of $Vav1^{-/-}$ NK cells via the same receptors (2B4, CD16, and NK1.1) did not result in normal cytotoxicity of FcR$^+$ P815 cells (Fig. 3 E). To better evaluate the dichotomy between cytokine production and cytotoxicity observed in $Vav1^{-/-}$ NK cells, we measured the levels of intracellular IFN-γ produced by wt and $Vav1^{-/-}$ NK cells 4 h after activation. This can be compared with the 4-h Cr-release assay used to measure cytotoxicity. No significant defect in IFN-γ production was detected, as similar percentages of wt and mutant NK cells stained positively for intracellular IFN-γ upon NK1.1 stimulation (Fig. 4 B). In contrast, CD3 stimulation did not result in IFN-γ production by $Vav1^{-/-}$ T cells (Fig. 4 B).

Table II. *$Vav1^{-/-}$ Mice Have a Reduced Capacity to Clear Tumor Cells*

|	wt	$Vav1^{-/-}$	$Rag2/\gamma c^{-/-}$
Mortality	0/4	1/6	3/5
Liver metastases in surviving mice	0/4	2/5	2/2

Mice were injected intravenously with 10^4 lymphoma cells (RDM4, H-2^k, class I^{low}), and survival was followed for 14 d. Those mice that survived were killed and examined for the presence of liver metastases.

1417 Colucci et al.
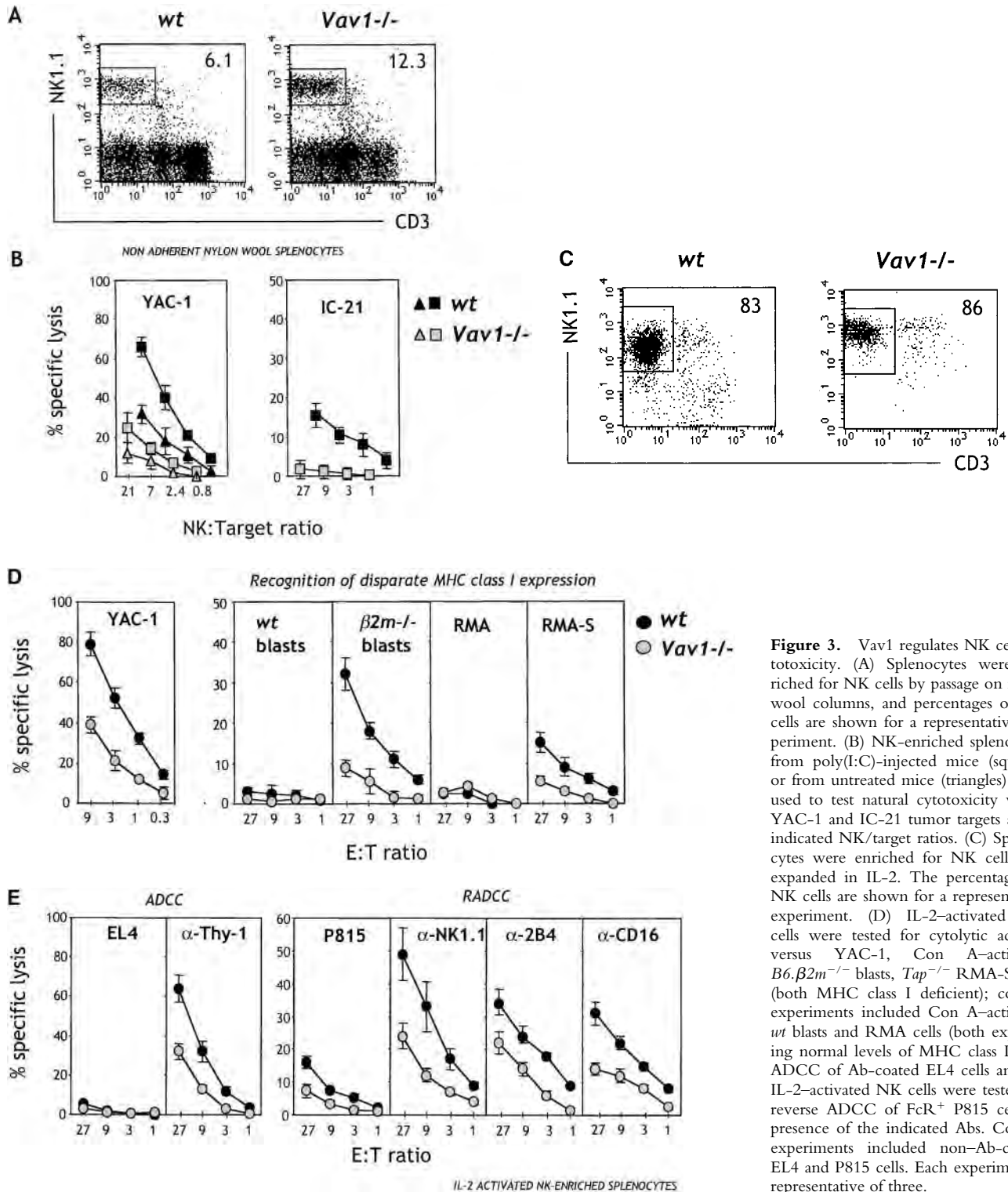
Figure 3. Vav1 regulates NK cell cytotoxicity. (A) Splenocytes were enriched for NK cells by passage on nylon wool columns, and percentages of NK cells are shown for a representative experiment. (B) NK-enriched splenocytes from poly(I:C)-injected mice (squares) or from untreated mice (triangles) were used to test natural cytotoxicity versus YAC-1 and IC-21 tumor targets at the indicated NK/target ratios. (C) Splenocytes were enriched for NK cells and expanded in IL-2. The percentages of NK cells are shown for a representative experiment. (D) IL-2–activated NK cells were tested for cytolytic activity versus YAC-1, Con A–activated $B6.\beta 2m^{-/-}$ blasts, $Tap^{-/-}$ RMA-S cells (both MHC class I deficient); control experiments included Con A–activated *wt* blasts and RMA cells (both expressing normal levels of MHC class I). (E) ADCC of Ab-coated EL4 cells and for IL-2–activated NK cells were tested for reverse ADCC of FcR^+ P815 cells in presence of the indicated Abs. Control experiments included non–Ab-coated EL4 and P815 cells. Each experiment is representative of three.

Vav1 Has Only a Minor Role in NK Cell Conjugate Formation. It has been shown that conjugate formation is decreased in human NK cell lines expressing a dominant-negative form of the Vav1 substrate Rac1 (32). We therefore tested the ability of $Vav1^{-/-}$ NK cells to form stable conjugates using a flow cytometric approach. As shown in

Fig. 5 A, conjugate formation by $Vav1^{-/-}$ NK cells was readily detectable, ruling out an essential role for Vav1 in this process. A detailed kinetic study revealed that $Vav1^{-/-}$ NK cells formed somewhat less conjugates, although the observed decrease never exceeded 30%, and was not statistically significant in four of five time points analyzed (Fig. 5

A

SORTED CELLS

B

IFN-γ
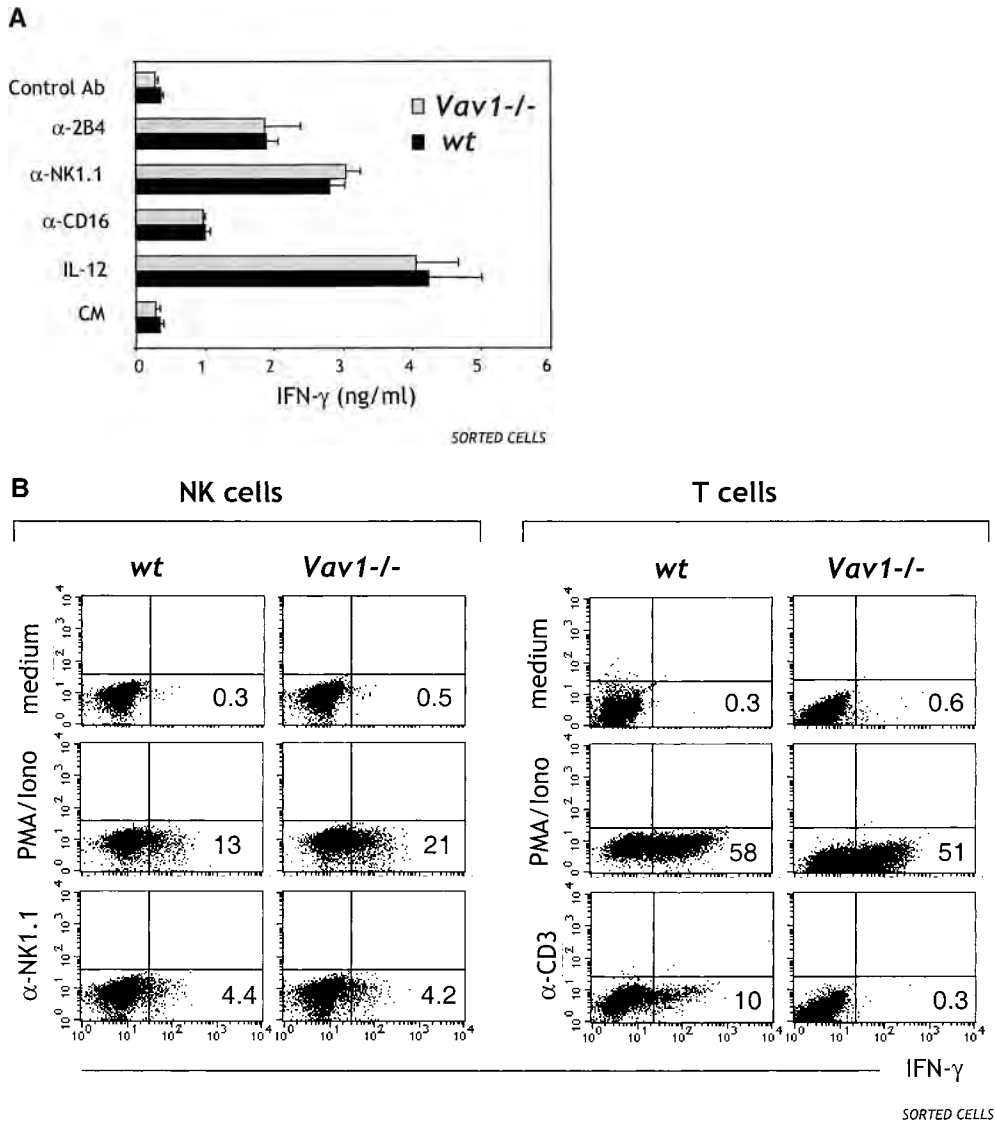
SORTED CELLS

Figure 4. Vav1 is dispensable for NK cell–mediated IFN-γ production. (A) Sorted IL-2–activated NK cells were incubated with different plate-bound antibodies or with IL-12. After 24 h, the amount of IFN-γ produced was measured by a standard ELISA. One representative experiment of two independent experiments performed. (B) Sorted IL-2–activated NK cells were incubated at 37°C with the indicated stimuli and thereafter stained for intracellular IFN-γ content.

B). Therefore, although Vav1 may be required for normal conjugate formation under these conditions, the extent of the lytic defect (up to 80% reduction), strongly suggests that postbinding mechanisms account for defective killer activity of $Vav1^{-/-}$ NK cells.

Vav1 Is Required to Initiate Calcium Flux in T Cells but Not in NK Cells. Vav1 is required for normal calcium flux in response to Ag–receptor signaling in T cells (26), and by analogy, reduced cytolysis by $Vav1^{-/-}$ NK cells could result from a similar defect in proximal signaling. To test this, we compared the rise in intracellular calcium in NK cells upon cross-linking membrane receptors. Normal calcium flux was induced after stimulation of the NK1.1 and CD16 receptors (Fig. 6) as well as the 2B4 and Ly49D receptors (data not shown) in both *wt* and $Vav1^{-/-}$ NK cells. In contrast, and as expected from previous reports (26), CD3 cross-linking did not induce calcium flux in $Vav1^{-/-}$ T cells (Fig. 6). Thus, Vav1 is not essential to transduce sig-

nals to the calcium pathway in NK cells and acts downstream of the rise in intracellular calcium to control the NK cell cytotoxicity machinery.

Vav1 Controls ERK Activation in NK and T Cells. Vav1 appears essential in transducing TCR signals to the ERK pathway in T cells (26), although studies using T cells from two other Vav1 mutant mice did not support an essential role for Vav1 in ERK activation (15, 16). ERKs have been implicated in the control of both cytotoxicity and IFN-γ production by NK cells (34–36). We therefore analyzed ERK1/2 phosphorylation in NK cells after stimulation of NK1.1 and compared it to CD3-initiated ERK1/2 phosphorylation in T cells. We found a reduced activation of ERK1 (eightfold) and ERK2 (2.5-fold) in $Vav1^{-/-}$ T cells (Fig. 7 A), confirming the essential role of Vav1 in TCR-mediated ERK activation (26). NK1.1-mediated ERK1 phosphorylation was 4.4-fold reduced in $Vav1^{-/-}$ NK cells, while no significant reduction in activation of ERK2
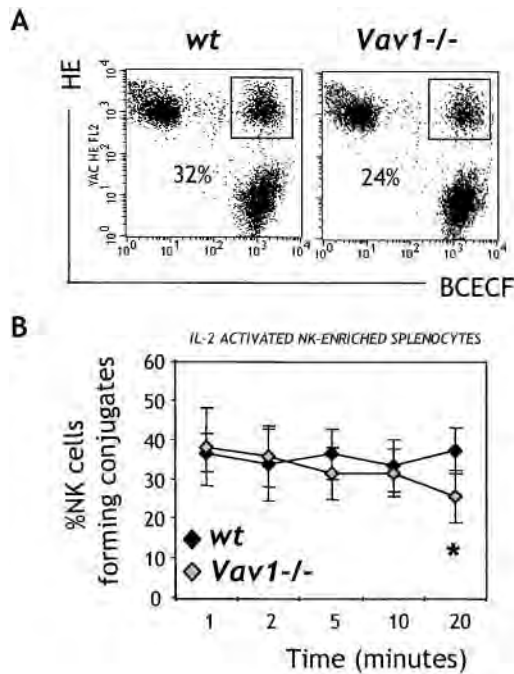
Figure 5. Vav1 plays a minor role in NK cell conjugate formation. (A) BCECF-labeled NK cells were allowed to form conjugates with HE-labeled YAC-1 targets for 20 min at 37°C and immediately analyzed by flow cytometry. Double-positive cells are conjugates, and the percentages (NK cells bound to targets out of the total NK cells) for the two genotypes are indicated for one representative of six independent experiments. Nonspecific aggregates were reproducibly <1%. (B) Kinetics of conjugate formation. Values at each time point were analyzed statistically, and significant differences ($P < 0.05$ by Student's t test) are indicated by an asterisk.

was detected (Fig. 7 A). However, stimulation of $Vav1^{-/-}$ NK cells via Ly49D resulted in reduced activation of both ERK1 (threefold) and ERK2 (twofold) kinases (data not shown). Collectively, these results suggest that Vav1 controls the ERK pathway in NK cells.

Vav1 Controls Exocytosis of Cytotoxic Granules upon Target Cell Binding. Intracellular polarization of NK cell cytotoxic granules toward sensitive target cells precedes granule

exocytosis. The Vav1/Rac1 pathway has been suggested to be a critical regulator of this process (32). To directly measure granule exocytosis upon contact with targets, we quantitated the granzyme A esterase content in the supernatants of NK cell cultures stimulated with targets. Although total esterase content was similar in *wt* and mutant NK cells (data not shown), $Vav1^{-/-}$ NK cells showed a significant reduction in esterase exocytosis compared with *wt* NK cells (7.2 ± 4.5 versus 17.3 ± 5%, $P = 0.03$; Fig. 7 B). Thus, the absence of Vav1 results in defective granule exocytosis and reduced ability to lyse tumor targets.

Discussion

The data presented here show that Vav1 is an essential regulator of NK cell–mediated cytolysis of tumor cells. On the other hand, Vav1 is dispensable for NK cell development and cytokine production. Thus, $Vav1^{-/-}$ mice generate normal numbers of phenotypically mature NK cells but show a dichotomy in NK cell–mediated effector functions. They are competent for IFN-γ–dependent control of early bacterial infections yet have a reduced capacity to reject tumors. We could define the cellular mechanisms that are *Vav1* dependent. The absence of Vav1 had only minor effects on conjugate formation, and calcium flux was normal. In contrast, the absence of Vav1 reduced ERK activation and exocytosis of cytotoxic granules that allow NK cells to lyse their targets.

The phenotype of NK cell functions in $Vav1^{-/-}$ mice is reminiscent of that of *Beige* mice, the murine model for Chediak-Higashi syndrome, a monogenic disease caused by mutations in the lysosomal trafficking regulator (*Lyst*) gene (50). Although the function of the Lyst protein has not yet been fully understood, it has been suggested to interact with microtubules to regulate protein sorting and late endosomal organization (51). Whatever the mechanisms underlying the Chediak-Higashi syndrome, the end result is a severely impaired granule exocytosis, much like what we have observed in $Vav1^{-/-}$ NK cells. Interactions between
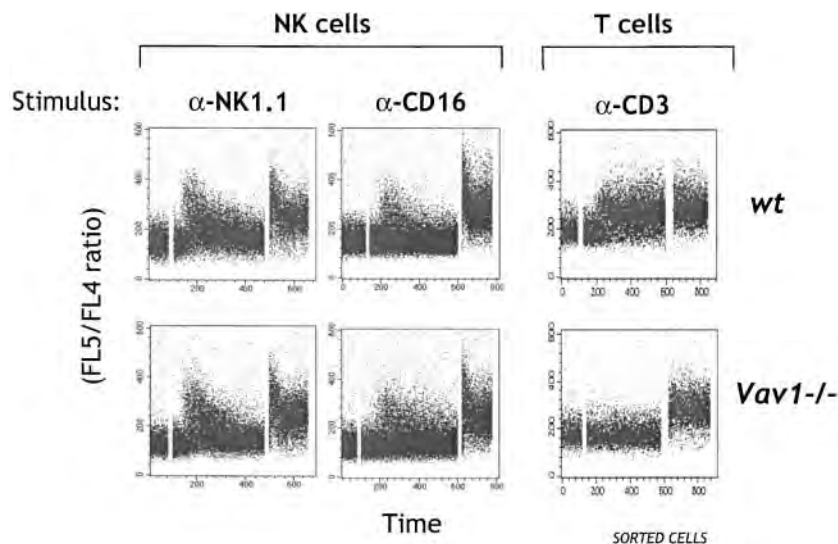
Figure 6. T cells but not NK cells require Vav1 to initiate calcium flux. Purified NK cells and T cells were stimulated with the primary mAbs (anti-NK1.1, anti-CD16, or anti-CD3), and analysis was done for 45 s to set the baseline levels of intracellular calcium. Acquisition was interrupted once to add cross-linking goat F(ab')$_2$ Abs and again to add 1 μg/ml of ionomycin. Cells were analyzed by LSR-FACS®. Intracellular calcium is proportional to the FL5/FL4 ratio.
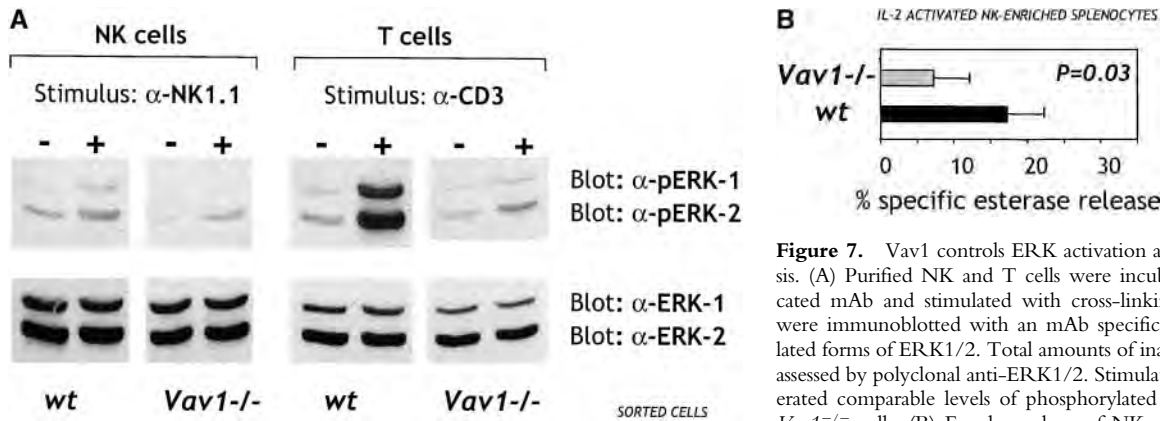
Figure 7. Vav1 controls ERK activation and granule exocytosis. (A) Purified NK and T cells were incubated with the indicated mAb and stimulated with cross-linking Abs. Cell lysates were immunoblotted with an mAb specific for the phosphorylated forms of ERK1/2. Total amounts of inactive ERK1/2 were assessed by polyclonal anti-ERK1/2. Stimulation with PMA generated comparable levels of phosphorylated ERK1/2 in *wt* and *Vav1*$^{-/-}$ cells. (B) Equal numbers of NK cells were stimulated with YAC-1 targets for 2 h and 30 min at 37°C. Supernatants were collected, and the specific release of esterase (granzyme A) was measured by using a BLT colorimetric assay, where the maximum release of esterase was obtained by freezing and thawing NK cells. Mean values ± SDs are shown from five independent experiments.

Vav1 and Lyst have never been documented, but it is likely that they both regulate components of the cytoskeleton (actin filaments and microtubules, respectively) required for successful exocytosis. However, NK cells of *Beige* mice have a complete defect in cellular cytotoxity, whereas NK cells of *Vav1*$^{-/-}$ mice have reduced capacity to kill tumor targets. How can we explain the quantitative defect in the lytic activity of *Vav1*$^{-/-}$ NK cells?

Cell-mediated cytotoxicity can be induced by calcium-dependent, perforin-mediated mechanisms and calcium-independent, FasL-mediated pathways (52). The residual cytotoxicity of *Vav1*$^{-/-}$ NK cells could be accounted for FasL-dependent mechanisms, which would not depend on exocytosis. In fact, we found that target cell lysis was totally abrogated in calcium-free medium in both *wt* and *Vav1*$^{-/-}$ NK cells (data not shown), ruling out calcium-independent mechanisms as responsible for the residual cytotoxic activity seen in *Vav1*$^{-/-}$ NK cells.

Activation of small GTPases can be induced by several GEFs, and functional redundancy among members of this family may account for some degree of compensation in the absence of Vav1. Human NK cells have been recently shown to express Vav2, which regulates the development of cell-mediated cytotoxicity (53). We have also detected Vav2 proteins in murine NK cells by intracellular staining (our unpublished observation), suggesting that suboptimal granule exocytosis and residual cytolysis by *Vav1*$^{-/-}$ NK cells may be accounted for by compensatory mechanisms (activation of Rac1 or Rho?) initiated by Vav2. The analysis of NK cell functions in mice deficient for Vav1 and Vav2 will help answer this question.

Inactivation of the Vav1 substrate Rac1 reduces the capacity of human NK cells to form stable conjugates with target cells (32). However, our data indicate only a minor role for Vav1 at this stage, suggesting essential roles for Vav1 in postbinding target cell lysis. Moreover, GEFs other than Vav1 may control Rac1-dependent conjugate formation, explaining the partial discrepancy between our results and those reported in the literature (32).

Our data underscore fundamentally divergent roles for Vav1 in the biology of T and NK lymphocytes. First, T and NK-T cell development and T cell functions are impaired in *Vav1*$^{-/-}$ mice, a consequence of the fact that T cells must signal through the same (Ag) receptor to complete differentiation and to exert their effector functions. Instead, requirement for Vav1 in NK cell functions (at least for cell-mediated cytotoxicity) dissociates from requirement for development. Several cytokine receptors are thought to drive NK cell differentiation (i.e., Flt3, c-kit, IL-7R, IL-15R), and we can suggest that Vav1 is not essential for transducing signals through any of these receptors, although it is phosphorylated upon ligation of some of them (23, 24). Moreover, it is likely that NK cell cytotoxicity is triggered by ligand–receptor systems different from those required for development, otherwise developing NK cells might be constitutively stimulated in the absence of inhibitory signals (which develop only later in life) and potentially dangerous.

Second, proximal signaling (measured by rise in intracellular calcium) in *Vav1*$^{-/-}$ NK cells is not impaired as opposed to defective capping and calcium flux upon cross-linking of TCRs in *Vav1*$^{-/-}$ T cells (14–16). Therefore, the abnormal biological responses of *Vav1*$^{-/-}$ T cells seem to be due to defective cellular activation. Along these lines, cytotoxic CD8$^+$ T cells of *Vav1*$^{-/-}$ mice fail to generate a primary response to viral infections, while they are able to mount a normal CTL secondary response, suggesting that Vav1 is required for T cell–mediated cytotoxicity only when the activation threshold is high, during a primary response (54). But this is unlikely to occur in *Vav1*$^{-/-}$ NK cells, as we show here that IL-2 activation in vitro and stimulation with poly(I:C) in vivo does not rescue the NK cell lytic defect. Although several receptors have been reported to be able to activate NK cell effector functions (55), the ones that activate natural cytotoxicity remain unknown (56). This incomplete knowledge has obviously been an obstacle for advancing our understanding of the molecular mechanisms transducing NK cell activating signals into ef-

1421   Colucci et al.

fector functions (57). The NK cell receptors we have used to elicit calcium flux (NK1.1, CD16, 2B4) are known to enhance cytotoxicity, but it would be interesting to measure rise in intracellular calcium upon target cell binding.

Vav1 has been shown to control the ERK pathway in T cells (26), using the same $Vav1^{-/-}$ mice analyzed in this study. However, two independent groups, using mice carrying different Vav1 mutations, did not find an essential role for Vav1 in ERK activation (15, 16). We confirm here the results by Costello et al. (26) showing that $Vav1^{-/-}$ T cells have a reduced ERK activation. Moreover, we show that Vav1 controls the ERK pathway in NK cells. Although both cytotoxicity and IFN-γ production have been shown to depend on ERK (34–36), we found that only cytotoxicity was affected in $Vav1^{-/-}$ NK cells. It is possible that different thresholds of ERK phosphorylation control cytokine productions and granule exocytosis, explaining the divergent effect seen in $Vav1^{-/-}$ NK cells.

Finally, receptor ligation in $Vav1^{-/-}$ NK cells resulted in divergent effects on tumor cell killing and on cytokine production, showing that Vav1 differentially controls NK cell effector functions. This situation is not paralleled in T cells, where TCR-initiated events tested so far (calcium flux, proliferation, apoptosis, IL-2 gene transcription, cytotoxicity) are all defective in the absence of Vav1 (14–16, 26). Our results are consistent with a functional dichotomy in NK cell signaling with respect to Vav1, where Vav1-dependent cytotoxicity contrasts with Vav1-independent cytokine production.

References

1. Collins, T.L., M. Deckert, and A. Altman. 1997. Views on Vav. *Immunol. Today*. 18:221–225.

2. Katzav, S., D. Martin-Zanca, and M. Barbacid. 1989. vav, a novel human oncogene derived from a locus ubiquitously expressed in hematopoietic cells. *EMBO J.* 8:2283–2290.

3. Bustelo, X.R., J.A. Ledbetter, and M. Barbacid. 1992. Product of vav proto-oncogene defines a new class of tyrosine protein kinase substrates. *Nature*. 356:68–71.

4. Margolis, B., P. Hu, S. Katzav, W. Li, R.J.M. Olive, A. Ullrich, A. Weiss, and J. Schlessinger. 1992. Tyrosine phosphorylation of vav proto-oncogene product containing SH2 domain and transcription factor motifs. *Nature*. 356:71–74.

5. Tarakhovsky, A., M. Turner, S. Schaal, P.J. Mee, L.P. Duddy, K. Rajewsky, and V.L. Tybulewicz. 1995. Defective antigen receptor-mediated proliferation of B and T cells in the absence of Vav. *Nature*. 374:467–470.

6. Adams, J.M., H. Houston, J. Allen, T. Lints, and R. Harvey. 1992. The hematopoietically expressed vav proto-oncogene shares homology with the dbl GDP-GTP exchange factor, the bcr gene and a yeast gene (CDC24) involved in cytoskeletal organization. *Oncogene*. 7:611–618.

7. Boguski, M.S., A. Bairoch, T.K. Attwood, and G.S. Michaels. 1992. Proto-vav and gene expression. *Nature*. 358: 113.

8. Crespo, P., X.R. Bustelo, D.S. Aaronson, O.A. Coso, M. Lopez-Barahona, M. Barbacid, and J.S. Gutkind. 1996. Rac-1 dependent stimulation of the JNK/SAPK signaling pathway by Vav. *Oncogene*. 13:455–460.

9. Olson, M.F., N.G. Pasteris, J.L. Gorski, and A. Hall. 1996. Faciogenital dysplasia protein (FGD1) and Vav, two related proteins required for normal embryonic development, are upstream regulators of Rho GTPases. *Curr. Biol.* 6:1628–1633.

10. Crespo, P., K.E. Schuebel, A.A. Ostrom, J.S. Gutkind, and X.R. Bustelo. 1997. Phosphotyrosine-dependent activation of Rac-1 GDP/GTP exchange by the vav proto-oncogene product. *Nature*. 385:169–172.

11. Cantrell, D. 1998. Lymphocyte signalling: a coordinating role for Vav? *Curr. Biol.* 8:R535–R538.

12. Fischer, K.D., A. Zmuldzinas, S. Gardner, M. Barbacid, A. Bernstein, and C. Guidos. 1995. Defective T-cell receptor signalling and positive selection of Vav-deficient CD4+ CD8+ thymocytes. *Nature*. 374:474–477.

13. Zhang, R., F.W. Alt, L. Davidson, S.H. Orkin, and W. Swat. 1995. Defective signalling through the T- and B-cell antigen receptors in lymphoid cells lacking the vav proto-oncogene. *Nature*. 374:470–473.

14. Turner, M., P.J. Mee, A.E. Walters, M.E. Quinn, A.L. Mellor, R. Zamoyska, and V.L. Tybulewicz. 1997. A requirement for the Rho-family GTP exchange factor Vav in positive and negative selection of thymocytes. *Immunity*. 7:451–460.

15. Fischer, K.D., Y.Y. Kong, H. Nishina, K. Tedford, L.E. Marengere, I. Kozieradzki, T. Sasaki, M. Starr, G. Chan, S. Gardener, et al. 1998. Vav is a regulator of cytoskeletal reorganization mediated by the T-cell receptor. *Curr. Biol.* 8:554–562.

16. Holsinger, L.J., I.A. Graef, W. Swat, T. Chi, D.M. Bautista, L. Davidson, R.S. Lewis, F.W. Alt, and G.R. Crabtree. 1998. Defects in actin-cap formation in Vav-deficient mice implicate an actin requirement for lymphocyte signal transduction. *Curr. Biol.* 8:563–572.

17. Kong, Y.Y., K.D. Fischer, M.F. Bachmann, S. Mariathasan, I. Kozieradzki, M.P. Nghiem, D. Bouchard, A. Bernstein, P.S. Ohashi, and J.M. Penninger. 1998. Vav regulates pep-

tide-specific apoptosis in thymocytes. *J. Exp. Med.* 188:2099–2111.

18. Williams, N.S., J. Klem, I.J. Puzanov, P.V. Sivakumar, J.D. Schatzle, M. Bennett, and V. Kumar. 1998. Natural killer cell differentiation: insights from knockout and transgenic mouse models and in vitro systems. *Immunol. Rev.* 165:47–61.

19. McKenna, H.J., K.L. Stocking, R.E. Miller, K. Brasel, T. De Smedt, E. Maraskovsky, C.R. Maliszewski, D.H. Lynch, J. Smith, B. Pulendran, et al. 2000. Mice lacking flt3 ligand have deficient hematopoiesis affecting hematopoietic progenitor cells, dendritic cells, and natural killer cells. *Blood.* 95:3489–3497.

20. Colucci, F., and J.P. Di Santo. 2000. The receptor tyrosine c-kit provides a critical signal for survival, expansion, and maturation of mouse natural killer cells. *Blood.* 95:984–991.

21. Kennedy, M.K., M. Glaccum, S.N. Brown, E.A. Butz, J.L. Viney, M. Embers, N. Matsuki, K. Charrier, L. Sedger, C.R. Willis, et al. 2000. Reversible defects in natural killer and memory CD8 T cell lineages in interleukin 15–deficient mice. *J. Exp. Med.* 191:771–780.

22. Moore, T.A., U. von Freeden Jeffry, R. Murray, and A. Zlotnik. 1996. Inhibition of gamma delta T cell development and early thymocyte maturation in IL-7 -/- mice. *J. Immunol.* 157:2366–2373.

23. Alai, M., A.L. Mui, R.L. Cutler, X.R. Bustelo, M. Barbacid, and G. Krystal. 1992. Steel factor stimulates the tyrosine phosphorylation of the proto-oncogene product, p95vav, in human hemopoietic cells. *J. Biol. Chem.* 267:18021–18025.

24. Dosil, M., S. Wang, and I.R. Lemischka. 1993. Mitogenic signalling and substrate specificity of the Flk2/Flt3 receptor tyrosine kinase in fibroblasts and interleukin 3-dependent hematopoietic cells. *Mol. Cell. Biol.* 13:6572–6585.

25. Trinchieri, G. 1989. Biology of natural killer cells. *Adv. Immunol.* 47:187–376.

26. Costello, P.S., A.E. Walters, P.J. Mee, M. Turner, L.F. Reynolds, A. Prisco, N. Sarner, R. Zamoyska, and V.L. Tybulewicz. 1999. The Rho-family GTP exchange factor Vav is a critical transducer of T cell receptor signals to the calcium, ERK, and NF-kappaB pathways. *Proc. Natl. Acad. Sci. USA.* 96:3035–3040.

27. Han, J., K. Luby-Phelps, B. Das, X. Shu, Y. Xia, R.D. Mosteller, U.M. Krishna, J.R. Falck, M.A. White, and D. Broek. 1998. Role of substrates and products of PI 3-kinase in regulating activation of Rac-related guanosine triphosphatases by Vav. *Science.* 279:558–560.

28. O'Rourke, L.M., R. Tooze, M. Turner, D.M. Sandoval, R.H. Carter, V.L. Tybulewicz, and D.T. Fearon. 1998. CD19 as a membrane-anchored adaptor protein of B lymphocytes: costimulation of lipid and protein kinases by recruitment of Vav. *Immunity.* 8:635–645.

29. Bonnema, J.D., L.M. Karnitz, R.A. Schoon, R.T. Abraham, and P.J. Leibson. 1994. Fc receptor stimulation of phosphatidylinositol 3-kinase in natural killer cells is associated with protein kinase C–independent granule release and cell-mediated cytotoxicity. *J. Exp. Med.* 180:1427–1435.

30. Wang, D., J. Feng, R. Wen, J.C. Marine, M.Y. Sangster, E. Parganas, A. Hoffmeyer, C.W. Jackson, J.L. Cleveland, P.J. Murray, et al. 2000. Phospholipase Cgamma2 is essential in the functions of B cell and several Fc receptors. *Immunity.* 13:25–35.

31. Xu, X., and A.S. Chong. 1996. Vav in natural killer cells is tyrosine phosphorylated upon cross-linking of Fc gamma RIIIA and is constitutively associated with a serine/threonine kinase. *Biochem. J.* 318:527–532.

32. Billadeau, D.D., K.M. Brumbaugh, C.J. Dick, R.A. Schoon, X.R. Bustelo, and P.J. Leibson. 1998. The Vav-Rac1 pathway in cytotoxic lymphocytes regulates the generation of cell-mediated killing. *J. Exp. Med.* 188:549–559.

33. Platanias, L.C., and M.E. Sweet. 1994. Interferon alpha induces rapid tyrosine phosphorylation of the vav proto-oncogene product in hematopoietic cells. *J. Biol. Chem.* 269:3143–3146.

34. Trotta, R., K.A. Puorro, M. Paroli, L. Azzoni, B. Bekele Abebe, L.C. Laurence, C. Eisenlohr, and B. Perussia. 1998. Dependence of both spontaneous and antibody-dependent, granule exocytosis-mediated NK cell cytotoxicity on extracellular signal-regulated kinases. *J. Immunol.* 161:6648–6656.

35. Milella, M., A. Gismondi, P. Roncaioli, L. Bisogno, G. Palmieri, L. Frati, M.G. Cifone, and A. Santoni. 1997. CD16 cross-linking induces both secretory and extracellular signal-regulated kinase (ERK)-dependent cytosolic phospholipase A2 (PLA2) activity in human natural killer cells: involvement of ERK, but not PLA2, in CD16-triggered granule exocytosis. *J. Immunol.* 158:3148–3154.

36. Wei, S., A.M. Gamero, J.H. Liu, A.A. Daulton, N.I. Valkov, J.A. Trapani, A.C. Larner, M.J. Weber, and J.Y. Djeu. 1998. Control of lytic function by mitogen-activated protein kinase/extracellular regulatory kinase 2 (ERK2) in a human natural killer cell line: identification of perforin and granzyme B mobilization by functional ERK2. *J. Exp. Med.* 187:1753–1765.

37. Trotta, R., K. Fettucciari, L. Azzoni, B. Abebe, K.A. Puorro, L.C. Eisenlohr, and B. Perussia. 2000. Differential role of p38 and c-Jun N-terminal kinase 1 mitogen-activated protein kinases in NK cell cytotoxicity. *J. Immunol.* 165:1782–1789.

38. Galandrini, R., G. Palmieri, M. Piccoli, L. Frati, and A. Santoni. 1999. Role for the Rac1 exchange factor Vav in the signaling pathways leading to NK cell cytotoxicity. *J. Immunol.* 162:3148–3152.

39. Colucci, F., C. Soudais, E. Rosmaraki, L. Vanes, V.L. Tybulewicz, and J.P. Di Santo. 1999. Dissecting NK cell development using a novel alymphoid mouse model: investigating the role of the c-abl proto-oncogene in murine NK cell differentiation. *J. Immunol.* 162:2761–2765.

40. Shinkai, Y., G. Rathbun, K.P. Lam, E.M. Oltz, V. Stewart, M. Mendelsohn, J. Charron, M. Datta, F. Young, A.M. Stall, et al. 1992. RAG-2-deficient mice lack mature lymphocytes owing to inability to initiate V(D)J rearrangement. *Cell.* 68:855–867.

41. Hoglund, P., R. Glas, C. Ohlen, H.G. Ljunggren, and K. Karre. 1991. Alteration of the natural killer repertoire in H-2 transgenic mice: specificity of rapid lymphoma cell clearance determined by the H-2 phenotype of the target. *J. Exp. Med.* 174:327–334.

42. Gaillot, O., E. Pellegrini, S. Bregenholt, S. Nair, and P. Berche. 2000. The ClpP serine protease is essential for the intracellular parasitism and virulence of *Listeria monocytogenes*. *Mol. Microbiol.* 35:1286–1294.

43. Colucci, F., M. Turner, E. Schweighoffer, D. Guy-Grand, V. Di Bartolo, M. Salcedo, V.L. Tybulewicz, and J.P. Di Santo. 1999. Redundant role of the syk protein tyrosine kinase in mouse NK cell differentiation. *J. Immunol.* 163:1769–1774.

44. Kim, S., and W.M. Yokoyama. 1998. NK cell granule exocytosis and cytokine production inhibited by Ly-49A engagement. *Cell. Immunol.* 183:106–112.

45. Dorfman, J.R., and D.H. Raulet. 1998. Acquisition of Ly49

receptor expression by developing natural killer cells. *J. Exp. Med.* 187:609–618.

46. Karre, K., H.G. Ljunggren, G. Piontek, and R. Kiessling. 1986. Selective rejection of H-2-deficient lymphoma variants suggests alternative immune defence strategy. *Nature.* 319: 675–678.

47. Smyth, M.J., K.Y.T. Thia, E.A. Street, E. Cretney, J. Trapani, M. Taniguchi, T. Kawano, S.B. Pelikan, N. Crowe, and D.I. Godfrey. 2000. Differential tumor surveillance by natural killer (NK) and NKT cells. *J. Exp. Med.* 191:661–668.

48. Biron, C.A., K.B. Nguyen, G.C. Pien, L.P. Cousens, and T.P. Salazar-Mather. 1999. Natural killer cells in antiviral defense: function and regulation by innate cytokines. *Annu. Rev. Immunol.* 17:189–220.

49. Wherry, J.C., R.D. Schreiber, and E.R. Unanue. 1991. Regulation of gamma interferon production by natural killer cells in scid mice: roles of tumor necrosis factor and bacterial stimuli. *Infect. Immun.* 59:1709–1715.

50. Barbosa, M.D., Q.A. Nguyen, V.T. Tchernev, J.A. Ashley, J.C. Detter, S.M. Blaydes, S.J. Brandt, D. Chotai, C. Hodgman, R.C. Solari, et al. 1996. Identification of the homologous beige and Chediak-Higashi syndrome genes. *Nature.* 382:262–265.

51. Faigle, W., G. Raposo, D. Tenza, V. Pinet, A.B. Vogt, H. Kropshofer, A. Fischer, G. de Saint-Basile, and S. Amigorena. 1998. Deficient peptide loading and MHC class II endosomal sorting in a human genetic immunodeficiency disease: the Chediak-Higashi syndrome. *J. Cell Biol.* 141:1121–1134.

52. Shresta, S., C.T. Pham, D.A. Thomas, T.A. Graubert, and T.J. Ley. 1998. How do cytotoxic lymphocytes kill their targets? *Curr. Opin. Immunol.* 10:581–587.

53. Billadeau, D.D., S.M. Mackie, R.A. Schoon, and P.J. Leibson. 2000. The rho family guanine nucleotide exchange factor vav-2 regulates the development of cell-mediated cytotoxicity. *J. Exp. Med.* 192:381–392.

54. Penninger, J.M., K.D. Fischer, T. Sasaki, I. Kozieradzki, J. Le, K. Tedford, K. Bachmaier, P.S. Ohashi, and M.F. Bachmann. 1999. The oncogene product Vav is a crucial regulator of primary cytotoxic T cell responses but has no apparent role in CD28-mediated co-stimulation. *Eur. J. Immunol.* 29: 1709–1718.

55. Lanier, L.L. 1998. NK cell receptors. *Annu. Rev. Immunol.* 16:359–393.

56. Moretta, A., R. Biassoni, C. Bottino, M.C. Mingari, and L. Moretta. 2000. Natural cytotoxicity receptors that trigger human NK–cell-mediated cytolysis. *Immunol. Today.* 21:228–234.

57. Leibson, P.J. 1997. Signal transduction during natural killer cell activation: inside the mind of a killer. *Immunity.* 6:655–661.