

Expression of Perforin and Serine Esterases by Human γ/δ T Cells

By Hiroataka Koizumi, Chau-Ching Liu, Li Mou Zheng, Sanjay V. Joag, Nancy K. Bayne,* Joseph Holoshitz,* and John Ding-E Young

From the Laboratory of Cellular Physiology and Immunology, The Rockefeller University, New York, New York 10021, and the *Division of Rheumatology, Department of Internal Medicine, University of Michigan Medical School, Ann Arbor, Michigan 48109

Summary

γ/δ T cells have recently been described in association with a number of disorders, including autoimmune diseases. γ/δ T cells are thought to play a cytotoxic role, but their mechanism of action is not known. Several granule mediators of cytotoxicity, including a pore-forming protein (perforin), and a family of serine esterases, have been isolated from cytotoxic T lymphocytes (CTL), lymphokine-activated killer (LAK) cells, and natural killer (NK) cells. We demonstrate here that γ/δ T cells also express these mediators. Northern blots show that γ/δ T cells express perforin, serine esterase 1 (SE 1), and SE 2. Three polyclonal antisera—raised against murine perforin, a peptide composed of amino acids 1–34 of human perforin, and human perforin expressed in bacteria—all reacted with a 70-kD protein in γ/δ T cells on Western blots. Immunostaining with antiperforin antisera shows that primary γ/δ T cells also contain perforin. Electron microscopy reveals that the granules of γ/δ T cells resemble those of CTL, LAK, and NK cells. γ/δ T cells also resemble LAK cells in possessing inclusion bodies in their nuclei. These results imply that γ/δ T cells resemble other cytolytic lymphocytes in their mechanism of action.

Cells with γ/δ TCRs (γ/δ T cells) generally exhibit MHC-unrestricted cytotoxicity *in vitro*. Target cells recognized by γ/δ T cells are markedly different from those recognized by CTL and by NK cells (1), suggesting that γ/δ T cells are a previously unrecognized type of killer lymphocyte. γ/δ T cells react with both the mycobacterial and the mammalian 65-kD heat shock protein (HSP65); this crossreactivity may be important in the pathogenesis of autoimmune diseases, including rheumatoid arthritis (RA) (2–4). The cytotoxic mechanisms of γ/δ T cells are not known, although several mediators of cytotoxicity have been described in other cytolytic lymphocytes (5–8). These mediators, present in the granules of CTL, NK cells, and lymphokine-activated killer (LAK) cells, include a pore-forming protein (PFP; perforin, cytolyisin), serine esterase 1 (SE 1; Hanukah Factor, granzyme A), and SE 2 (granzyme B). We used Northern blots, immunoblots, and immunostaining to determine whether γ/δ T cells also contain these cytotoxic mediators.

Materials and Methods

Cells. Human γ/δ T cell clones 1.2, 1.3, 1.4, and 4.1 (all TCR- α/β^- , $-\gamma/\delta^+$, CD3⁺, CD4⁻, CD8⁻) were derived from the synovial fluid of a patient with RA as described (2). γ chain cDNA

sequencing data showed common use of V₉-J_p rearrangements with junctional diversity among clones, suggesting that the four clones were distinct clonal populations (Loh, E., J. Holoshitz, and S. Strober, manuscript in preparation). Human LAK cells were prepared by stimulating plastic nonadherent PBMC for 10 d with 1,000 U/ml of rIL-2 (Cetus Corp., Emeryville, CA). Human peripheral blood NK cells stimulated with IL-2 were generously provided by Dr. Bice Perussia (Wistar Institute, Philadelphia, PA).

Cytotoxicity Assays. Standard 4-h ⁵¹Cr release assays (9) were performed using tumor lines K562, Daudi, and autologous (JBEB) or heterologous (DSEB) EBV-transformed B cell lines as targets.

cDNA Probes and Northern Blot Analysis. ³²P-labeled cDNA probes specific for perforin, SE 1, SE 2, and γ -actin were prepared and hybridized sequentially with total RNA blots on nylon membranes as described (9).

Antibodies and Immunoblot Analysis. Rabbit polyclonal antiperforin antisera were generated against purified mouse perforin (10), human perforin expressed in bacteria (11), and against a synthetic peptide (pN1-34) composed of amino acids 1–34 of human perforin. The peptide was immobilized on nitrocellulose, mixed with Freund's adjuvant, and 10–15 μ g was injected subcutaneously into rabbits; five booster injections were given. Immunoblotting was done exactly as described (9).

Immunostaining. CD4⁻, CD8⁻ plastic nonadherent PBMC selected by panning were cultured for 3 d with 500 U/ml of rIL-2 (12), stained with TCR- δ 1 mAb (T Cell Sciences, Cambridge, MA) and sorted using a FACStar[®] (Becton Dickinson & Co., Mountain

View, CA). Sorted cells (referred to as primary γ/δ T cells) were 97% pure on FACS analysis. Primary γ/δ T cells were cytocentrifuged, and stained sequentially with antiperforin antiserum and FITC-conjugated goat anti-rabbit IgG (Fab')₂ (Tago Inc., Burlingame, CA).

Electron Microscopy. Clone 1.4 cells were fixed with an equal volume of 4% glutaraldehyde and 2% paraformaldehyde in 0.1 M cacodylate buffer, pH 7.2, postfixed with 2% OsO₄, dehydrated in a graded ethanol series, and embedded in Epon 812. Ultra-thin sections stained with uranyl acetate and lead citrate were examined in an electron microscope.

Results and Discussion

Cytotoxicity of γ/δ T Cells. γ/δ T cell clones displayed MHC-unrestricted cytotoxicity against both NK-resistant (Daudi) and NK-sensitive (K562) target cell lines (Fig. 1). However, no cytolytic activity could be found with autologous or heterologous EBV-transformed B cell lines (Fig. 1),

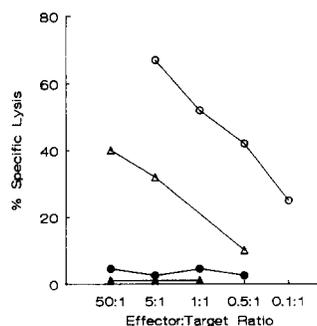


Figure 1. Cytotoxicity of γ/δ T cells. γ/δ T cells were tested for cytolytic activity on ⁵¹Cr-labeled tumor lines Daudi (open circles), K562 (open triangles), and on two EBV-transformed B cell lines: JBEB (autologous; closed circles) and DSEB (heterologous; closed triangles).

suggesting that the cytolytic activity of these cells was antigen specific and MHC independent.

γ/δ T Cells Express Perforin and Serine Esterases. Northern blots of γ/δ T cell clones (Fig. 2 a; data shown for clone 1.4) showed that they expressed mRNAs for perforin, SE 1, SE 2, and actin. The size of the expressed messages was the same as that seen in human LAK cells used as a control (12). Daudi cells (Fig. 2 a) and a panel of tumor cell lines (not shown; see reference 12) did not express mRNAs for perforin or SEs.

These results were further confirmed by immunoblot analysis (Fig. 2 b) using three perforin-specific antisera raised against human perforin expressed in *Escherichia coli*, a peptide composed of amino acids 1–34 of human perforin, and purified murine perforin (not shown). All three antisera reacted specifically with human NK cells, CTLL-R8, and all four clones of γ/δ T cells (data shown only for clone 1.4); but not with K562 cells, or YAC-1 cells (not shown). Pre-immune antisera did not react with any of the cell lysates tested. To establish the presence of perforin in primary γ/δ T cells, we used immunostaining of a FACS-sorted population that was 97% pure. As seen in Fig. 3, primary γ/δ T cells stained with antiperforin antisera showed a granular pattern similar to that seen with CTL and NK cells. Three independent lines of evidence (Northern blots, Western blots with three antisera raised against different forms of perforin, and immunostaining of primary γ/δ T cells with anti-perforin antisera) all suggest that γ/δ T cells express perforin. Perforin has now been shown to be produced by all cytotoxic effector lymphocytes. Our results, obtained with clonal and primary cell populations, are the first definitive study reporting perforin expression in γ/δ T cells.

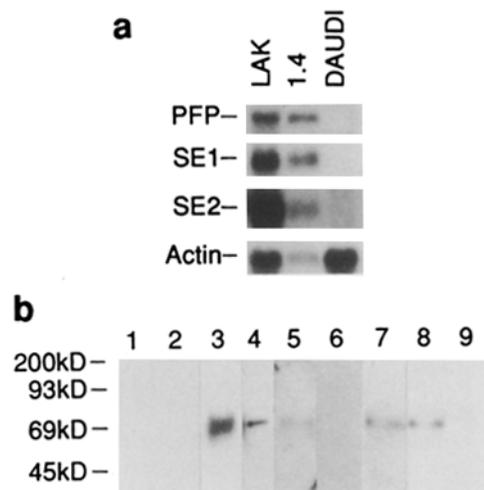


Figure 2. Expression of perforin, SE 1, and SE 2 by γ/δ T cells. (a) Northern blot analysis of total RNA from human LAK cells (lane 1), γ/δ T cells (lane 2), and Daudi cells (lane 3) with cDNA probes specific for perforin, SE 1, SE 2, and actin. (b) Immunoblot analysis of human NK cells (lanes 1, 4, and 8), γ/δ T cells (lanes 2, 5, and 7), CTLL-R8 (lane 3), and K562 (lanes 6 and 9), with preimmune serum (lanes 1 and 2), antiserum raised against perforin expressed in bacteria (lanes 3–6), and antiserum raised against an NH₂-terminal peptide of human perforin (lanes 7–9).

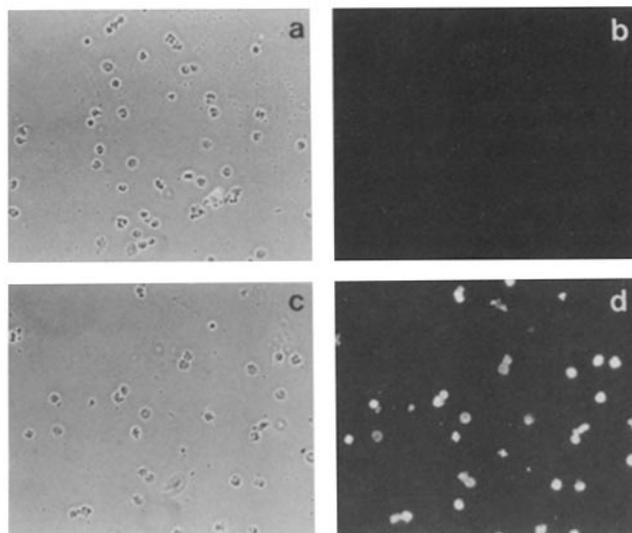


Figure 3. Immunofluorescence staining of primary γ/δ T cells using antiperforin antibody. Primary γ/δ T cells, enriched by cell sorting (97% pure), were stained with preimmune serum (b) or with antiperforin antiserum (d). Corresponding phase contrast micrographs are shown in a and c.

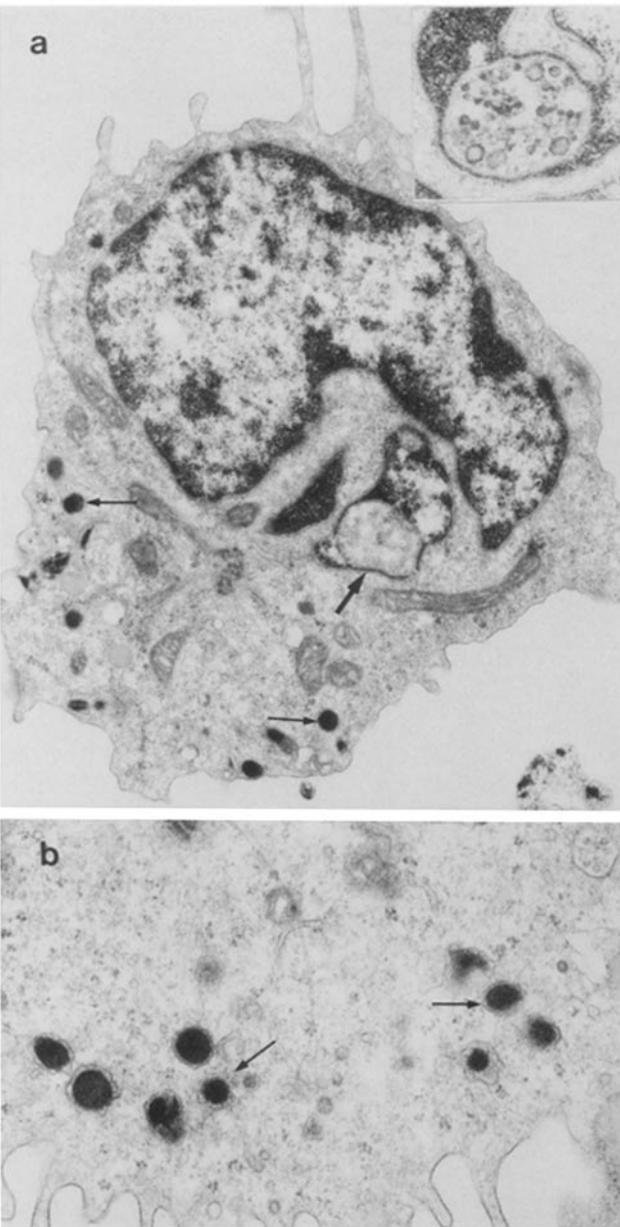


Figure 4. (a) Ultrastructure of a γ/δ T cell. The large arrow indicates an inclusion body in the nucleus. Small arrows show cytoplasmic granules ($\times 10,000$). Inset demonstrates a typical inclusion body, composed of membrane-like structures and electron-dense particles. (b) High magnification of cytoplasmic granules. The granules are bound by a single membrane and contain the dense cores with numerous surrounding vesicles ($\times 23,000$).

Ultrastructure of γ/δ T Cells. γ/δ T cells possess long microvilli, well-developed mitochondria, elongated rough endoplasmic reticulum, and 100–160-nm granules surrounded by a single membrane (Fig. 4, a and b). The granules are composed of a central core of electron-dense fine material surrounded by numerous membrane-bound vesicles and resemble those seen in CTL and NK cells. The nuclei are irregular and are rich in chromatin concentrated near the nuclear membrane. Many nuclei contain one or two inclusion bodies (IB) that consist of membrane-like structures, electron-dense particles, and free ribosomes bound by a double membrane complex (Fig. 3 a, inset). Similar IB were found recently in human LAK cells by Groscurth et al. (13). They suggest that the IB are derived from endoplasmic reticulum, contain glycogen, and represent overstimulation of LAK cells with IL-2. As LAK cells are a heterogeneous population that includes γ/δ T cells (14), it is possible that IB are specifically associated with γ/δ T cells. We are attempting to resolve this issue using immunoelectron microscopy of LAK cells with anti-TCR- γ/δ antibodies.

γ/δ T cells may be implicated in RA and other autoimmune diseases. In RA patients, large numbers of γ/δ T cells are found in the synovial fluid of affected joints (2, 4). This observation, together with our finding that γ/δ T cells contain perforin and SEs, suggests the possibility that γ/δ T cell-mediated destruction of joint tissue is of importance in the pathology of RA. Increased numbers of γ/δ T cells are also seen in pulmonary sarcoidosis (15), ataxia-telangiectasia (16), leprosy and leishmaniasis (17), atopic dermatitis (18), and Chediak-Higashi syndrome (19), suggesting that γ/δ T cells play a role in a number of immunologic disorders.

A significant role for granule mediators in cell killing is supported by the fact that antigenic or mitogenic signals known to induce cytotoxic effectors also induce mRNAs for perforin and SEs in T cells (12, 20). The present results therefore strongly support the inclusion of γ/δ T cells along with CTL, NK, and LAK cells as cytolytic lymphocytes.

We thank Drs. I. L. Weissman, and J. A. Trapani for providing some of the probes used here, and Drs. Z. A. Cohn and R. M. Steinman for constant support and for critical reading of this manuscript.

This work was supported in part by grants from the Irvington Institute for Medical Research, the American Cancer Society (New York City Division), the American Heart Association (New York City Affiliate), Michigan Chapter of the Arthritis Foundation, and U.S. Public Health Service grant CA-47307. C.-C. Liu is a Fellow of the Irvington Institute. L. M. Zheng is a Lalor Foundation Fellow. J. Holoshitz is

a Searle Scholar and a recipient of the Arthritis Investigator Award. J. D.-E Young is a Lucille P. Markey Scholar.

Address correspondence to Hirotaka Koizumi, Laboratory of Cellular Physiology and Immunology, The Rockefeller University, 1230 York Avenue, New York, NY 10021.

Received for publication 6 August 1990 and in revised form 18 October 1990.

References

1. Thiele, D.L., and P.E. Lipsky. 1989. The role of cell surface recognition structures in the initiation of MHC-unrestricted 'promiscuous' killing by T cells. *Immunol. Today*. 10:375.
2. Holoshitz, J., F. Koning, J.E. Coligan, J. De Bruyn, and S. Strober. 1989. Isolation of CD4⁻CD8⁻ mycobacteria-reactive T lymphocyte clones from rheumatoid arthritis synovial fluid. *Nature (Lond.)*. 339:226.
3. Born, W., L. Hall, A. Dallas, J. Boymel, T. Shinnick, D. Young, P. Brennan, and R. O'Brien. 1990. Recognition of a peptide antigen by heat shock-reactive $\gamma\delta$ T lymphocytes. *Science (Wash. DC)*. 249:67.
4. Kaufmann, S.H.E. 1990. Heat shock proteins and the immune response. *Immunol. Today*. 11:129.
5. Henkart, P.A. 1985. Mechanism of lymphocyte-mediated cytotoxicity. *Annu. Rev. Immunol.* 3:31.
6. Podack, E.R. 1985. The molecular mechanism of lymphocyte-mediated tumor cell lysis. *Immunol. Today*. 6:21.
7. Tschopp, J., and C.V. Jongeneel. 1988. Cytotoxic T lymphocyte mediated cytolysis. *Biochemistry*. 27:2641.
8. Young, J.D.-E. 1989. Killing of target cells by lymphocytes: A mechanistic view. *Physiol. Rev.* 69:250.
9. Liu, C.-C., M. Steffen, F. King, and J.D.-E Young. 1987. Identification, isolation, and characterization of a novel cytotoxin in murine cytolytic lymphocytes. *Cell*. 51:393.
10. Persechini, P.M., and J.D.-E Young. 1988. The primary structure of the lymphocyte pore-forming protein perforin: partial amino acid sequencing and determination of isoelectric point. *Biochem. Biophys. Res. Commun.* 156:740.
11. Young, L.H.Y., S.V. Joag, L.M. Zheng, C.P. Lee, Y.S. Lee, and J.D.-E Young. 1990. Perforin-mediated myocardial damage in acute myocarditis. *Lancet*. 336:1019.
12. Liu, C.-C., S. Rafii, A. Granelli-Piperno, J.A. Trapani, and J.D.-E Young. 1989. Perforin and serine esterase gene expression in stimulated human T cells. Kinetics, mitogen requirements, and effects of cyclosporin A. *J. Exp. Med.* 170:2105.
13. Groscurth, P., S. Diener, R. Stahel, L. Jost, D. Kagi, and H. Hengartner. 1990. Morphologic analysis of human lymphokine-activated killer (LAK) cells. *Int. J. Cancer*. 45:694.
14. Testa, U., A. Care, E. Montesoro, C. Fossati, R. Masciulli, M. Fagiolo, D. Bulgarini, D. Habetswallner, G. Isacchi, P.G. Pelicci, and C. Peschle. 1990. Interleukin-2-dependent long-term cultures of low-density lymphocytes allow the proliferation of lymphokine-activated killer cells with natural killer, T γ/δ or TNK phenotype. *Cancer Immunol. Immunother.* 31:11.
15. Balbi, B., D.R. Moller, M. Kirby, K.J. Holroyd, and R.G. Crystal. 1990. Increased numbers of T lymphocytes with $\gamma\delta$ -positive antigen receptors in a subgroup of individuals with pulmonary sarcoidosis. *J. Clin. Invest.* 85:1353.
16. Carbonari, M., M. Cherchi, R. Paganelli, G. Giannini, E. Galli, C. Gaetano, C. Papetti, and M. Fiorilli. 1990. Relative increase of T cells expressing the gamma/delta rather than the alpha/beta receptor in ataxia-telangiectasia. *N. Engl. J. Med.* 322:73.
17. Modlin, R.L., C. Pirmez, F.M. Hofman, V. Torigian, K. Ueyamura, T.H. Rea, B.R. Bloom, and M.B. Brenner. 1989. Lymphocytes bearing antigen-specific $\gamma\delta$ T-cell receptors accumulate in human infectious disease lesions. *Nature (Lond.)*. 339:544.
18. de Paloli, P., D. Gennari, G. Basaglia, P. Martelli, and G. Santini. 1990. Phenotypic analysis of a CD2⁻CD3⁺ T cell receptor gamma delta lymphocyte subset. *Immunol. Lett.* 23:195.
19. Holcombe, R.F., R. van de Griend, S.-L. Ang, R.L.H. Bolhuis, and J.G. Seidman. 1990. Gamma-delta T cells in Chediak-Higashi syndrome. *Acta Haematol. (Basel)*. 83:193.
20. Joag, S.V., C.-C. Liu, B.S. Kwon, W.R. Clark, and J.D.-E Young. 1990. Expression of mRNAs for pore-forming proteins and two serine esterases in murine primary and cloned effector lymphocytes. *J. Cell. Biochem.* 43:1.