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Natural killer T cell recognition of lipid antigens

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Abstract

Natural killer T cells recognize lipid antigens in the context of CD1 molecules. Recent publications show that this mode of recognition differs substantially from that of classic T-cell receptor peptide-major histocompatibility complex interaction.

Introduction and context

The recognition of lipids and glycolipids by the immune system was exclusively focused on antibody production until Brenner's group [1] described the recognition of mycobacterial lipids by human αβ T cells restricted on CD1b. Until then, the common admission was that T cells were tolerized against the main lipid components of cells and lipid mediators; the possible recognition of foreign lipids by CD4 or CD8 T cells was not even considered. The admission that CD1 molecules [2] may bind lipid was not settled until the first structure of a CD1 molecule revealed an antigen-binding groove unsuited to peptide binding [3] but ideal for lipid interactions as it is lined with hydrophobic residues [4]. During the same period, it was discovered that natural killer T (NKT) cells were restricted on CD1 [5] and that a natural product extracted from marine sponge could stimulate NKT cells in a CD1-restricted manner [6]. This situation shifted the entire field of anti-lipid immunity from the recognition of lipid/CD1 complexes by classical αβ and γδ T cells toward the exclusive niche of NKT biology and semi-invariant T-cell recognition. This choice has proven very beneficial by concentrating the effort on a very simplified model system. Indeed, NKT cells are innate regulatory T cells essential for the initial coordination of immune responses. As such, they express a semi-invariant T-cell receptor (TCR), which certain consider a pattern recognition receptor [7,8], made of a unique α chain conserved between species (Vα14 in mice and Vα24 in humans) and a limited set of Vβ chains (8.2, 7, and 2 in mice and 11 in humans). Serendipity brought an unusual exogenous agonist of NKT, alpha-galactosylceramide (αGalCer), to the field that allowed, in sequence, the development of CD1 tetramers capable of detecting NKT cells and the discovery of similar bacterial ligands capable of stimulating NKT during the course of infection. These developments were vital for the rapid advances in the field of cellular immunology of NKT cells as well as chemistry of NKT ligands and structural biology of CD1 and semi-invariant TCR. The search for endogenous ligands that drive thymic selection as well as normal innate stimulation of NKT cells during the course of immune responses has remained more elusive and brings forward some critical structural considerations that will be discussed in the concluding paragraph.

Major recent advances

Our understanding of the recognition of CD1 lipid complexes by semi-invariant TCR has progressed rapidly over the past 2 years with the determination of CD1/αGalCer structures [9,10], Vα14 and Vα24 TCR structures [11,12], and finally the uncovering of the Vα24/CD1 αGalCer complex structure [8,13]. We need to keep in mind that most of our knowledge is focused on the recognition of αGalCer and αGalCer-like ligands, a family of exogenous antigens found only in *Sphingomonas*, *Ehrlichia*, and probably a very limited set of other bacteria [14,15].

On the CD1 side, the mode of binding of phospholipids and glycolipids is now well understood and appears to

be universal [16]. The head group of the lipid is accessible for TCR interaction, and its orientation is critically influenced by the chemical nature of its linkage to the acyl chains (glycerol versus ceramide and α versus β). The acyl chains of the lipid occupy the groove of the CD1 molecule and impose some discrete but noticeable conformational changes of the groove [10,17] that may influence T-cell recognition to some extent [18].

The structures of Vα24 and Vα14 TCRs alone were as expected for αβ TCR and only confirmed the high homology between human and murine receptors [11,12]. The architecture of the Vα24 TCR/CD1-αGalCer revealed a dramatic parallel docking of TCR over CD1 at the very end of its binding groove, an arrangement never seen before; this footprint placed the complementarity-determining regions (CDRs) of the α chain next to the protruding α-linked galactose of the ligand [13]. One should not overreact about this apparently unusual docking or try to over-interpret it. Indeed, the more TCR/major histocompatibility complex (MHC) structures we have, the more variations we see in the overall mode of docking, with some extreme situations now described for MHC class II/TCR complexes. These great variations in docking batter, to some extent, the concept of genomic 'interaction codons' that was developed for Vβ8.2 TCR/peptide-MHC recognition [20] since the Vβ8.2 of NKT receptors does not respect that same recognition mode. However, the most important finding brought about by the elucidation of the first Vα24 TCR/CD1-αGalCer and now Vα14 TCR/CD1-αGalCer structures is the ideal placement of the α chain next to the galactose of αGalCer and the dominance of recognition by CDR1 and CDR3α loops. Interestingly enough, these structures also revealed that the β chain is playing some accessory role in binding by revealing the participation of the CDR2β and CDR3β loops in the overall footprint. Given the sequence similarities between CDR2β of Vβ8.2 and Vβ7, the influence of single-residue mutagenesis was evaluated with respect to TCR/CD1 affinity. Whereas the higher affinity of the Vβ8.2 retaining TCR could not be improved, a single change in Vβ7 (S54→A) was capable of increasing the affinity four-fold, indicating that the CDR2β of Vβ7 was suboptimal. However, it is too early to conclude that this affinity difference is sufficient to explain the preferential usage of Vβ8 over Vβ7 in the mouse NKT repertoire. Indeed, if one looks at the human system where Vβ11 is used almost exclusively, TCR/CD1-αGalCer has a much lower affinity than its murine counterpart, and it is likely that some other Vβ could pair just as well with Vα24 to achieve such a low-affinity interaction; but they do not. More importantly, measurements carried out with αGalCer as the CD1-bound ligand might have no relevance to the thymic situation and repertoire selection of NKT cells. Indeed, this process will be driven by CD1 bound to natural unknown ligands which might have no chemical relationship to αGalCer whatsoever. It is still interesting to argue the opposite situation (that the CD1-αGalCer measurements are relevant) and propose that lipid recognition by semi-invariant TCR will obey the same set of rules for binding independently of the CD1-bound lipid. The fact that the hierarchy of Vβ usage is identical for hybridomas stimulated with CD1α-GalCer and CD1-iGb3 (CD1 isoglobotrihexosylceramide) may support the argument [21]. However, again, caution is required as different approaches have come to different conclusions and were arguing that the repertoire of CD1-iGb3-reactive cells was much more restricted than that of αGalCer-restricted cells [22].

Future directions

Have all of the questions regarding the semi-invariant TCR recognition of CD1 lipid complexes been answered? Of course not, even though it is clear that for the particular ligand that is αGalCer, we have a very good understanding of the molecular events that led to its detection. However, two essential paradigms remain poorly understood and largely unexplored and will require attention and investment: (a) the recognition of CD1 lipid complexes by non-semi-invariant TCR and (b) the recognition of endogenous selecting and activating ligands. With respect to point (a), it is important to remember that the recognition of bacterial lipids in a CD1-restricted manner by 'normal' αβ and γδ T cells was the first established link between lipids and T cells [1]. Ever since, the recognition of exogenous lipids by T cells has not been studied as extensively. The main reasons for this situation are simple: lack of reagents (for example, tetramers or animal models [23]) and the inability to immunize efficiently against lipids. Consequently, we do not know how to efficiently expand these T-cell populations *in vivo*, and even if we did, we would be unable to follow them. The second challenge faced by researchers in the field is just as daunting: discovering endogenous ligands. As compelling as the argument is about iGb3 being one of the endogenous NKT ligands [24], it is quite obvious that other ligands remain to be discovered. However, what is not obvious is the approach amenable to their discovery. Genetic analysis has proven unfruitful, with the exception of iGb3, and biochemistry and direct isolation are mostly limited by the fact that we do not know what we are looking for (a classic chicken-egg problem in lipid chemistry). At this point, new screening methods must be explored or we will all have to hope that serendipity strikes again like it did in the discovery of αGalCer.

Abbreviations

αGalCer, alpha-galactosylceramide; CDR, complementarity-determining region; iGb3, isoglobotrihexosylceramide; MHC, major histocompatibility complex; NKT, natural killer T; TCR, T-cell receptor.

Competing interests

The author declares that he has no competing interests.

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References

1. Beckman EM, Porcelli SA, Morita CT, Behar SM, Furlong ST, Brenner MB: **Recognition of a lipid antigen by CD1-restricted alpha beta$^+$ T cells.** *Nature* 1994, **372:**691-4.
2. Calabi F, Milstein C: **A novel family of human major histocompatibility complex-related genes not mapping to chromosome 6.** *Nature* 1986, **323:**540-3.
3. Castaño AR, Tangri S, Miller JE, Holcombe HR, Jackson MR, Huse WD, Kronenberg M, Peterson PA: **Peptide binding and presentation by mouse CD1.** *Science* 1995, **269:**223-6.
4. Zeng Z, Castaño AR, Segelke BW, Stura EA, Peterson PA, Wilson IA: **Crystal structure of mouse CD1: an MHC-like fold with a large hydrophobic binding groove.** *Science* 1997, **277:**339-45.
5. Bendelac A, Lantz O, Quimby ME, Yewdell JW, Bennink JR, Brutkiewicz RR: **CD1 recognition by mouse NK1$^+$ T lymphocytes.** *Science* 1995, **268:**863-5.
6. Kawano T, Cui J, Koezuka Y, Toura I, Kaneko Y, Motoki K, Ueno H, Nakagawa R, Sato H, Kondo E, Koseki H, Taniguchi M: **CD1d-restricted and TCR-mediated activation of valpha14 NKT cells by glycosylceramides.** *Science* 1997, **278:**1626-9.
7. Scott-Browne JP, Matsuda JL, Mallevaey T, White J, Borg NA, McCluskey J, Rossjohn J, Kappler J, Marrack P, Gapin L: **Germline-encoded recognition of diverse glycolipids by natural killer T cells.** *Nat Immunol* 2007, **8:**1105-13.
8. Pellicci DG, Patel O, Kjer-Nielsen L, Pang SS, Sullivan LC, Kyparissoudis K, Brooks AG, Reid HH, Gras S, Lucet IS, Koh R, Smyth MJ, Mallevaey T, Matsuda JL, Gapin L, McCluskey J, Godfrey DI, Rossjohn J: **Differential recognition of CD1d-alpha-galactosyl ceramide by the V beta 8.2 and V beta 7 semi-invariant NKT T cell receptors.** *Immunity* 2009, **31:**47-59.
9. Zajonc DM, Cantu C 3rd, Mattner J, Zhou D, Savage PB, Bendelac A, Wilson IA, Teyton L: **Structure and function of a potent agonist for the semi-invariant natural killer T cell receptor.** *Nat Immunol* 2005, **6:**810-8.
10. Koch M, Stronge VS, Shepherd D, Gadola SD, Mathew B, Ritter G, Fersht AR, Besra GS, Schmidt RR, Jones EY, Cerundolo V: **The crystal structure of human CD1d with and without alpha-galactosylceramide.** *Nat Immunol* 2005, **6:**819-26.
11. Gadola SD, Koch M, Marles-Wright J, Lissin NM, Shepherd D, Matulis G, Harlos K, Villiger PM, Stuart DI, Jakobsen BK, Cerundolo V, Jones EY: **Structure and binding kinetics of three different human CD1d-alpha-galactosylceramide-specific T cell receptors.** *J Exp Med* 2006, **203:**699-710.

   F1000 Factor 3.0 *Recommended*
   Evaluated by Jamie Rossjohn 19 Apr 2006

12. Zajonc DM, Savage PB, Bendelac A, Wilson IA, Teyton L: **Crystal structures of mouse CD1d-iGb3 complex and its cognate Valpha14 T cell receptor suggest a model for dual recognition of foreign and self glycolipids.** *J Mol Biol* 2008, **377:**1104-16.
13. Borg NA, Wun KS, Kjer-Nielsen L, Wilce MC, Pellicci DG, Koh R, Besra GS, Bharadwaj M, Godfrey DI, McCluskey J, Rossjohn J: **CD1d-lipid-antigen recognition by the semi-invariant NKT T-cell receptor.** *Nature* 2007, **448:**44-9.

   F1000 Factor 8.6 *Exceptional*
   Evaluated by David Branch Moody 03 Jul 2007, Edward Collins 17 Jul 2007, Toshinori Nakayama 26 Jul 2007, Jia-huai Wang 30 Jul 2007, Moriya Tsuji 15 Oct 2007

14. Mattner J, Debord KL, Ismail N, Goff RD, Cantu C 3rd, Zhou D, Saint-Mezard P, Wang V, Gao Y, Yin N, Hoebe K, Schneewind O, Walker D, Beutler B, Teyton L, Savage PB, Bendelac A: **Exogenous and endogenous glycolipid antigens activate NKT cells during microbial infections.** *Nature* 2005, **434:**525-9.

   F1000 Factor 9.8 *Exceptional*
   Evaluated by Eric Vivier 08 Apr 2005, Richard Locksley11 Apr 2005, David Branch Moody 18 Apr 2005

15. Kinjo Y, Wu D, Kim G, Xing GW, Poles MA, Ho DD, Tsuji M, Kawahara K, Wong CH, Kronenberg M: **Recognition of bacterial glycosphingolipids by natural killer T cells.** *Nature* 2005, **434:**520-5.

   F1000 Factor 8.0 *Exceptional*
   Evaluated by Eric Vivier 08 Apr 2005, David Branch Moody 18 Apr 2005

16. Zajonc DM, Wilson IA: **Architecture of CD1 proteins.** *Curr Top Microbiol Immunol* 2007, **314:**27-50.
17. Zajonc DM, Elsliger MA, Teyton L, Wilson IA: **Crystal structure of CD1a in complex with a sulfatide self antigen at a resolution of 2.15 A.** *Nat Immunol* 2003, **4:**808-15.
18. McCarthy C, Shepherd D, Fleire S, Stronge VS, Koch M, Illarionov PA, Bossi G, Salio M, Denkberg G, Reddington F, Tarlton A, Reddy BG, Schmidt RR, Reiter Y, Griffiths GM, van der Merwe PA, Besra GS, Jones EY, Batista FD, Cerundolo V: **The length of lipids bound to human CD1d molecules modulates the affinity of NKT cell TCR and the threshold of NKT cell activation.** *J Exp Med* 2007, **204:**1131-44.
19. Wucherpfennig KW, Call MJ, Deng L, Mariuzza R: **Structural alterations in peptide-MHC recognition by self-reactive T cell receptors.** *Curr Opin Immunol* 2009, **21:**590-5.
20. Feng D, Bond CJ, Ely LK, Maynard J, Garcia KC: **Structural evidence for a germline-encoded T cell receptor-major histocompatibility complex interaction 'codon'.** *Nat Immunol* 2007, **8:**975-83.
21. Mallevaey T, Scott-Browne JP, Matsuda JL, Young MH, Pellicci DG, Patel O, Thakur M, Kjer-Nielsen L, Richardson SK, Cerundolo V, Howell AR, McCluskey J, Godfrey DI, Rossjohn J, Marrack P, Gapin L: **T cell receptor CDR2 beta and CDR3 beta loops collaborate functionally to shape the iNKT cell repertoire.** *Immunity* 2009, **31:**60-71.
22. Wei DG, Curran SA, Savage PB, Teyton L, Bendelac A: **Mechanisms imposing the Vbeta bias of Valpha14 natural killer T cells and consequences for microbial glycolipid recognition.** *J Exp Med* 2006, **203:**1197-207.
23. Felio K, Nguyen H, Dascher CC, Choi HJ, Li S, Zimmer MI, Colmone A, Moody DB, Brenner MB, Wang CR: **CD1-restricted adaptive immune responses to Mycobacteria in human group 1 CD1 transgenic mice.** *J Exp Med* 2009, **206:**2497-509.

   F1000 Factor 3.0 *Recommended*
   Evaluated by Andrea Cooper 08 Oct 2009

24. Zhou D, Mattner J, Cantu C 3rd, Schrantz N, Yin N, Gao Y, Sagiv Y, Hudspeth K, Wu YP, Yamashita T, Teneberg S, Wang D, Proia RL, Levery SB, Savage PB, Teyton L, Bendelac A: **Lysosomal glycosphingolipid recognition by NKT cells.** *Science* 2004, **306:**1786-9.

   F1000 Factor 9.6 *Exceptional*
   Evaluated by Grant Morahan 06 Dec 2004, Randy Brutkiewicz 21 Dec 2004