Role of KIR3DS1 in Human Diseases

The Harvard community has made this article openly available. Please share how this access benefits you. Your story matters.

| Citation         | Körner, Christian, and Marcus Altfeld. 2012. Role of KIR3DS1 in human diseases. Frontiers in Immunology 3:326. |
|------------------|-------------------------------------------------------------------------------------------------------------|
| Published Version| doi:10.3389/fimmu.2012.00326                                                                                   |
| Citable link     | http://nrs.harvard.edu/urn-3:HUL.InstRepos:10579243                                                            |
| Terms of Use     | This article was downloaded from Harvard University’s DASH repository, and is made available under the terms and conditions applicable to Other Posted Material, as set forth at http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#LAA |
Role of KIR3DS1 in human diseases

Christian Körner and Marcus Altfeld*
Ragon Institute of Massachusetts General Hospital, Massachusetts Institute of Technology and Harvard University, Charlestown, MA, USA

INTRODUCTION

Killer-immunoglobulin (Ig)-like receptors (KIRs) represent a family of activating and inhibitory receptors expressed on natural killer (NK) cells that shape and regulate NK cell functions (Moretta et al., 1993). All human KIRs share common structural features including a cytoplasmic domain, a transmembrane domain and either two or three Ig-like extracellular domains (D0, D1, and D2). Each of these structural domains has a functional role with regards to ligand specificity and signal transduction after engagement of the respective receptor. Based on the number of extracellular domains, KIR proteins are classified as KIR2D (two domains) and KIR3D (three domains) receptors. KIR2D receptors can be further subdivided into a type I and type II group depending on the characteristics of the two extracellular domains. Type I KIR2D proteins, such as KIR2DL1-3 and KIR2DS1-5, exhibit a D2 and D1 domain. In contrast, KIR2DL4 and KIR2DL5 encode for type II KIR2D protein lacking the D1 domain but comprising a D0 domain similar to the membrane-distal domain of KIR3D proteins. The intracellular domains of KIRs feature either a short or a long cytoplasmic tail (S or L in the nomenclature, respectively). The long cytoplasmic tail contains two immune tyrosine-based inhibitory motifs (ITIM) which lead to the transduction of an inhibitory signal and thus defines inhibitory KIRs. In contrast, KIR genes encoding for activating receptors possess short cytoplasmic tails, which have a positively charged amino acid residue in their transmembrane region. This allows recruitment of the DAP12 adaptor molecule that contains an immunoreceptor tyrosine-based activating motif (ITAM) and transmits an activating signal. An exception is KIR2DL4, which contains only one ITIM within the long cytoplasmic tail and additionally possesses a charged residue, thus, making it capable of triggering both inhibitory and activating signals (Faure and Long, 2002).

The function of natural killer (NK) cells is controlled by several activating and inhibitory receptors, including the family of killer-immunoglobulin-like receptors (KIRs). One distinctive feature of KIRs is the extensive number of various haplotypes generated by the gene content within the KIR gene locus as well as by highly polymorphic members of the KIR gene family, namely KIR2DL1/S1. Within the KIR2DL1/S1 gene locus, KIR2DS1 represents a conserved allelic variant and displays other unique features in comparison to the highly polymorphic KIR2DL1 allele. KIR3DS1 is present in all human populations and belongs to the KIR haplotype group B. KIR3DS1 encodes for an activating receptor featuring the characteristic short cytoplasmic tail and a positively charged residue within the transmembrane domain, which allows recruitment of the ITAM-bearing adaptor molecule DAP12. Although HLA class I molecules are thought to represent natural KIR ligands, and HLA-Bw4 molecules serve as ligands for KIR2DL1, the ligand for KIR3DS1 still needs to be identified. Despite the lack of formal evidence for an interaction of KIR3DS1 with HLA-Bw4-I80 or any other HLA class I subtype to date, a growing number of associations between the presence of KIR3DS1 and the outcome of viral infections have been described. Especially, the potential protective role of KIR3DS1 in combination with HLA-Bw4-I80 in the context of HIV-1 infection has been studied intensively. In addition, a number of recent studies have associated the presence or absence of KIR3DS1 with the occurrence and outcome of some malignancies, autoimmune diseases, and graft-versus-host disease (GVHD). In this review, we summarize the present knowledge regarding the characteristics of KIR3DS1 and discuss its role in various human diseases.

Keywords: KIR3DS1, HLA, HIV-1, killer-immunoglobulin-like receptors, NK cell
A and B, which not only reflect differences in their gene content and genes and absence of the above genes, respectively. In contrast to the KIR haplotype A, which is defined by the presence of at least one of the following genes: KIR2DL5*, KIR3DL1*, KIR3DS1*, KIR2DS5*, and KIR3DS1. Haplotype A is defined by the absence of the above genes, respectively. In contrast to the KIR haplotype A, in which genetic variability is created by a broad allelic variance within each KIR gene, variability within B haplotypes is achieved by the presence or absence of most of the activating KIR genes and KIR2DL5. Hence, alleles of activating KIRs account only for a minority of KIR alleles (March et al., 2003; Robinson et al., 2010). This suggests a general evolutionary concept in which allelic variance of activating KIRs is either limited by natural selection or not required because of the vast possible combinations resulting from gene arrangements. An alternative hypothesis is that the limited diversification of activating KIRs simply reflects the shorter time period since the first appearance of activating KIRs as compared to the ancestral inhibitory KIR proteins. Nevertheless, KIR haplotype group A as well as group B are present in all human populations indicating an evolutionary advantage for the maintenance of both haplotype groups (Gendzickhade et al., 2006, 2009).

The KIR3D1/S1 gene locus displays a unique feature of containing reciprocal subsets of allotypes encoding either for the inhibitory receptor KIR3D1 or the activating receptor KIR3DS1 (Campbell and Puszy, 2011). While KIR3D1 allotypes exhibit a high rate of single nucleotide polymorphisms (SNPs), KIR3DS1 is almost monomorphic (Norman et al., 2007; Parham et al., 2011). As a consequence, most of the approximately 70 known allotypes of KIR3D1/S1 account for KIR3DS1. Because of its opposing functional characteristic in comparison to KIR3D1, KIR3DS1 was initially considered to be the product of a discrete gene (Valiante et al., 1997). However, further segregation studies identified KIR3DS1 as a functional allele of the KIR3D1/S1 gene locus (Marsh et al., 2003; Tralferne et al., 2010).

The evolutionary history of KIR3D1/S1 can be traced back before the radiation of the placental mammals, approximately 135 million ago. The ancestral founder gene KIR3D diverged upon gene duplication into KIR3DL and KIR3DS (Sambeook et al., 2006; Guethlein et al., 2007). While KIR3DSX remained a pseudogene within the leukocyte Ig-like receptors (LILR) gene locus, KIR3DL expanded and evolved rapidly through duplication and recombination forming diverse lineages within simian primates. Based on ancestral inhibitory KIRs with their characteristic ITIMs located within the long cytoplasmic tail, the appearance of KIRs with activating properties resulted from new mutations within the TM and the cytoplasmic tail (Abi-Rached and Parham, 2005). Elimination of ITIMs that account for the suppressive properties of inhibitory KIRs resulted from mutations or stop codons leading to alterations of length of the cytoplasmic tail. This process was accompanied by the introduction of a positively charged amino acid residue within the TM allowing activating KIRs to interact with the DAP12 adaptor molecule, which possesses an ITAM (Lanier et al., 1998; Vivier et al., 2004).

Based on sequences as well as on the presence and frequency of KIR3D1/S1 allotypes in the human populations, KIR3D1/S1 alleles can be classified into three distinct phylogenetic lineages that evolved more than 3 million years ago: 3DL1*015-like, 3DL1*005-like, and 3DS1*015-like (Norman et al., 2007; Parham et al., 2011). In line with this, the allotypes KIR3DL1*015, KIR3DL1*005, and 3DS1*015 each represent the prototypical alleles of the lineages due to their abundance in all human populations. Although KIR3DS1*015 is the most abundant KIR3D1/S1 allele worldwide, lower allele frequencies of KIR3DS1 in sub-Saharan Africans have been described, indicating that natural selection for inhibitory alleles of KIR3D1/S1 is potentially due to increased exposure to a wide variety of pathogens over a long time period (Norman et al., 2007). In this context, Abi-Rached and Parham (2005) introduced a provocative hypothesis that might provide an explanation for the maintenance and diversification of activating KIRs as a result of balanced selection of the KIR haplotype groups A and B (enriched for activating KIRs) observed in modern human populations. The authors postulated that activating KIRs undergo an initial phase of positive selection, which is driven by an increased resistance to pathogens and reproductive success. This phase is then followed by a period of negative selection that is caused by the negative effects of autoimmunity. Although the presence and maintenance of both KIR haplotype groups A and B in all human populations are in line with this
With the exception of KIR2DL4, the promoters within this region are highly homologous throughout the KIR locus (Wilson et al., 2000). The expression of the encoded KIR genes is regulated by the degree of DNA methylation, which prevents transcription in the early stages of NK cell development (Chan et al., 2005; Santourlidis et al., 2008). During maturation and education of NK cells, the KIR expression pattern of each NK cell is thought to be defined by hypo- or hypermethylation of the distinct promoters (Santourlidis et al., 2002; Chan et al., 2003). The level of expression of KIR3DL1/S1 is determined by a complex interplay of the activity of two promoters within the intergenic region upstream of KIR3DL1/S1. While the distal promoter only transcribes sense mRNA, the proximal promoter features a bidirectional promoter activity, producing either sense or antisense mRNA in a probabilistic fashion resulting in either silenced or increased expression of KIR3DL1/S1 (Stewart et al., 2003; van Bergen et al., 2005; Davies et al., 2007; Stubberg et al., 2007). SNPs within the proximal promoters determine the activity and transcription of sense and antisense mRNA, resulting in different expression levels and frequencies of the different KIR3DL1/S1 alleles (Yawata et al., 2006; Li et al., 2008).

However, these SNPs can only partially explain the discordant observation of low transcription ratio and frequency of KIR3DS1 in NK cells. Depending on homo- or heterozygosity of the KIR3DS1 allele, the frequency of NK cells expressing KIR3DS1 can range between ∼40–80 and 10–60% respectively (O’Connor et al., 2007; Pascal et al., 2007). This indicates the involvement of other factors influencing KIR3DS1 expression on NK cells. In fact, it has been shown that surface expression of KIR3DS1 can be induced by various stimuli, such as IL-2, IL-15, or the MHC class I deficient K562 cell line (Morvan et al., 2009). Moreover, Yawata et al. (2006) observed increased numbers of NK cells expressing KIR3DL1 and KIR3DS1 in individuals carrying the cognate HLA ligands, indicating a possible effect of HLA ligands on the expression of their respective KIR receptors. Finally, frequency and surface density of KIR3DS1 can be further affected by copy number variants of KIR3DL1/S1 within the KIR locus (Pelak et al., 2011). Increased RNA expression and percentage of KIR3DS1+ NK cells but not KIR3DL1+ NK cells were observed in individuals with multiple copies of KIR3DL1 alleles, suggesting an interaction between the expression levels of these two allotypes that will require further investigations.

Surface expression of KIR3DS1 can be detected by the KIR3DL1/S1-specific mAb Z27 (Carr et al., 2007; O’Connor et al., 2007; Trundle et al., 2007). In combination with the KIR3DL1-specific mAb DX9 (Litvin et al., 1994), mAb Z27 is used to discriminate cells with regards to their surface expression of KIR3DL1 or KIR3DS1. While Z27 and DX9 antibodies both stain KIR3DL1, KIR3DS1 is not recognized by DX9, indicating that the antibodies target different epitopes. In line with this, it has been shown that Tyr199 is a determinant for DX9 recognition of KIR3DL1 but not for Z27 (Khakoo et al., 2002). Furthermore, different amino acid residues in position 199 of KIR3DL1 (proline) and KIR3DS1 (leucine) might contribute to the observed different staining profiles. KIR3DS1 displays low fluorescence intensity when stained with Z27. Whether this reflects a low binding affinity of Z27 to KIR3DS1 or an overall low surface expression of KIR3DS1 in comparison to KIR3DL1 is unclear. In contrast, KIR3DL1 displays various expression levels depending on the respective allotype, which can be discerned into alleles with high (e.g., KIR3DL1*001) and low surface density (e.g., KIR3DL1*005), as well as a null variant (KIR3DL1*004) that is not expressed on the cell surface (Gardiner et al., 2001; Pardo et al., 2003; Yawata et al., 2006). Of note, similar to the KIR3DL1*004 allele that encodes for a KIR3DL1 molecule that is not expressed on the cell surface, a KIR3DS1null allele (KIR3DS1*049N) has also been identified (Pascal et al., 2007). A complex deletion/substitution mutation in exon 4 resulting in a premature stop codon was identified as the underlying mechanism. A subsequent study analyzing allele frequencies of KIR3DS1*049N in the different populations worldwide revealed that this allele is very rare, suggesting that KIR3DS1*049N is probably not importantly involved in disease associations described for KIR3DS1 (Martin et al., 2007a).

Despite these recent advances in our understanding of the regulation of KIR expression on a single cell level, the underlying mechanisms of how the KIR expression patterns are shaped are still not fully understood. In general, cytokines and the presence of cognate HLA ligands may be involved during maturation and education of NK cells thus influencing KIR expression patterns within the NK cell population. With regards to KIR3DS1, further studies are needed to fully understand how expression of KIR3DS1 is regulated and to determine the potential functional consequences of increased expression.

**Ligand Specificity of KIR3DL1 and KIR3DS1**

Classical and non-classical HLA class I molecules can serve as natural ligands for several inhibitory and activating KIRs (Biasioli et al., 1995; Rajagopalan and Long, 1999; Hansasuta et al., 2004). Moreover, crystal structures of certain KIR/peptide/HLA complexes have clarified the molecular interactions between KIR and peptide-loaded HLA molecules (Borysion et al., 2000; Van et al., 2001; Vievan et al., 2011), including the KIR3DL1 and HLA-B57 pair.
KIR3DL1 recognizes HLA-A and -B molecules containing the HLA-Bw4 motif (Cella et al., 1994; Gumperz et al., 1995; Stern et al., 2008). However, KIR3DL1 displays differential affinities to its cognate HLA class I ligands depending on the encoding KIR3DL1 allele, the respective HLA allele, and the HLA class I-presented epitope (Carr et al., 2005; Thananthai et al., 2007; Foley et al., 2008; Fadda et al., 2011). Minor changes in the amino acid sequence of KIR3DL1 in regions interacting with the peptide/HLA complex can lead to either increased affinity or complete abrogation of binding. Two polymorphisms at position 238 (D2 domain) and 320 (TM) that discriminate KIR3DL1*002 and KIR3DL1*007 were identified to affect the ability of HLA-Bw4 ligands to inhibit KIR3DL1*002- and KIR3DL1*007-expressing NK leukemia cell lines (Carr et al., 2005). Moreover, it has been shown that the differential binding of KIR3DL1 to HLA-A*2402 in complex with an HLA-I peptide is mediated by dimorphic motifs in the D0 and D1/D2 domains of KIR3DL1 (Sharma et al., 2009). Thus, single amino acid substitutions within KIR3DL1 play a critical role in the binding affinity to HLA ligands and can provide insights into the molecular mechanisms that regulate KIR/HLA interactions. In addition, it has been shown that a single amino acid change in the KIR2D receptors defines the ability of KIR2D receptors to recognize either HLA-C group 1 or 2 receptors. This suggests a unifying concept of ligand specificity and affinity for KIR proteins (Winter and Long, 1997; Moesta et al., 2008).

The binding affinity of KIR3DL1 to its cognate HLA class I molecules is further dependent on the HLA class I presented peptides. In particular, amino acid residues in position 7 and 8 of the HLA-bound peptide seem to be pivotal in either promoting or abrogating binding of KIRs to their cognate HLA class I molecules (Peruzzi et al., 1996; Mandelboim et al., 1997; Rajagopalan and Long, 1997; Vales-Gomez et al., 1998; Hanssutta et al., 2004; Fadda et al., 2010). In this context, it has been shown that binding of KIR3DL1 to HLA-B*0701 was affected by a variety of HIV-1-derived peptides (Fadda et al., 2011). Crystal structures of KIR/HLA/peptide complexes confirmed a direct interaction between residues 7 and 8 of the HLA-presented peptide and KIRs (Boyington et al., 2000; Vivian et al., 2011). Overall, amino acid polymorphisms within KIR proteins and HLA class I-presented epitopes represent two pivotal mechanisms defining the binding of KIR proteins to their cognate HLA ligands. These polymorphisms might provide NK cells with an ability to distinguish changes of the epitope repertoire presented by HLA class I on virus-infected and transformed cells.

Despite a high sequence homology (~95%) between KIR3DS1 and KIR3DL1 (Dohring et al., 1996), direct binding of KIR3DS1 to HLA class I molecules has not been convincingly demonstrated to date. However, several genetic studies have suggested a functional interaction between KIR3DS1 and HLA-Bw4 molecules in human diseases (Martin et al., 2002; Lopez-Vazquez et al., 2005). Martin et al. (2002) first identified an association between KIR3DS1 and certain HLA-B alleles and the progression to AIDS. The combined presence of KIR3DS1 and HLA-B alleles that encode an isoleucine at position 80 (HLA-Bw4-180) was associated with significantly slower progression to AIDS, while the absence of either KIR3DS1 or HLA-Bw4-180 allele led to the loss of the observed effect. The combined KIR3DS1+/HLA-Bw4-180 genotype was also associated with decreased susceptibility for the development of hepatocellular carcinoma in patients with chronic hepatitis C virus (HCN; Lopez-Vazquez et al., 2005). These data implicate a potential interaction between HLA-Bw4-180 molecules and KIR3DS1, and suggested a functional role for KIR3DS1 in NK cell-mediated recognition of HIV-1-infected as well as transformed cells. However, not all studies have demonstrated a synergistic protective effect of the compounded genotype in the context of HIV-1 infection. Other groups have shown that the beneficial effects of HLA-Bw4-180 and KIR3DS1 are independent and not linked to each other (Barbour et al., 2007), or have observed a detrimental effect of carriage of KIR3DS1 on progression of HIV-1 infection (Gaudieri et al., 2005).

Based on these genetic associations studies, several groups have sought to assess a direct interaction of KIR3DS1 and HLA-Bw4-180 class I molecules. Gillespie et al. (2007) used multiple Bw4-I80 MHC class I tetramers refolded with a broad panel of HIV-1 peptide epitopes to detect tetramer binding to KIR3DS1 transiently expressed on 293-T cells, while O’Connor et al. (2007) used a luciferase reporter assay to detect activation of KIR3DS1-transfected Jurkat cells in response to stimulation with 271.221 cells transfected with multiple HLA-Bw4 molecules. Although these methods were successfully used to identify HLA/peptide complexes as ligands for KIR3DL1, the same assays failed to show any detectable interaction with KIR3DS1. Another approach was chosen by Carr et al. (2007) using KIR3DS1–IgG fusion constructs to identify binding with HLA-B*5701-transfected 721.221 cells. Again, the authors were not able to identify HLA-Bw4-180 as ligands for KIR3DS1. In contrast to KIR3DL1, NK cells, proliferation and cytotoxic capacity of KIR3DS1+ NK cells were not affected by HLA-Bw4* irritated allogeneic EBV-B cell lines (Morvan et al., 2008, 2009).

The one exception is a recent study by Li et al. (2010) suggesting interactions between KIR3DS1 and HLA-Bw4-T80 allotype HLA-B*2705 by using surface plasmon resonance (SPR) technology. However, there were some limitations in the design of these studies, including the lack of negative controls that demonstrate that binding of KIR3DS1 to the HLA/peptide complex is specific. Overall, additional studies will be needed to determine whether KIR3DS1 can bind to HLA-Bw4 molecules, and whether these interactions depend on the HLA class I-presented epitope.

These studies which have investigated the allele-specific characteristics of KIR3DL1 have provided helpful insights in the potential molecular interaction between KIR3DS1 and HLA-Bw4 molecules (see Table 1). Despite the high level of homology to KIR3DL1, KIR3DS1 differs in at least six amino acid positions throughout the extracellular domains, including positions 163, 166 (D1 domain), and 199 (D2 domain; Gardiner et al., 2001). Introduction of any of these KIR3DS1-specific amino acid residues into a KIR3DL1*001 molecule as performed by Sharma et al. (2009) led to complete abrogation of binding to HLA-A*2402, a confirmed ligand for KIR3DL1. In this context, Thomas et al. (2008) identified a natural KIR3DL1 allotype (KIR3DL1*004) that shares the same amino acid residues at position 138, 163, and 166 of the D1 domain with KIR3DS1*013. Introduction of these single amino acid substitutions at position 138, 163, and 166 into
Table 1 | Effects of selected amino acid variations within KIR3DL1/S1 on antibody recognition and HLA binding.

| Domain | Position | 3DS1* | 3DL1* | Effect on antibody staining and HLA binding | Reference |
|--------|----------|-------|-------|-------------------------------------------|-----------|
| D0     | 58       | G     | S     | DX9 and Z27 binding: reduction a          | Sharma et al. (2009) |
| D0     | 92       | M     | V     | DX9 and Z27 binding: reduction a          | Sharma et al. (2009) |
| D1     | 138      | W     | G     | DX9 and Z27 binding: no effect a          | Sharma et al. (2009, O’Connor et al. (2011) |
|        |          |       |       | Tetramer binding (HLA-B*5701): no effect c | Vivian et al. (2011) |
|        |          |       |       | Tetramer binding (HLA-A*2402): reduction a| O’Connor et al. (2011) |
|        |          |       |       | Tetramer binding (HLA-B*2705): abrogation c| O’Connor et al. (2011) |
| D1     | 163      | S     | P     | DX9 and Z27 binding: no effect a          | Sharma et al. (2009, O’Connor et al. (2011) |
|        |          |       |       | Tetramer binding (HLA-A*2402): abrogation c| Sharma et al. (2009, O’Connor et al. (2011) |
|        |          |       |       | Tetramer binding (HLA-B*5701): reduction a| O’Connor et al. (2011) |
| D1     | 166      | R     | L     | DX9 binding: reduction a                  | Sharma et al. (2009) |
|        |          |       |       | Tetramer binding (HLA-A*2402): abrogation c| Sharma et al. (2009, O’Connor et al. (2011) |
|        |          |       |       | Tetramer binding (HLA-B*5701): reduction a| O’Connor et al. (2011) |
| D2     | 199      | L     | P     | DX9 and Z27 binding: no effect a          | Sharma et al. (2009) |
|        |          |       |       | Tetramer binding (HLA-A*2402): abrogation c| Sharma et al. (2009) |
|        |          |       |       | Tetramer binding (HLA-B*5701): reduction a| O’Connor et al. (2011) |

aAmino acid residue of KIR3DS1*013 and KIR3DS1*018, respectively.
bTetramers folded with the following peptides: HLA-B*5701: LSSPVTKSF (self peptide), HLA-A*2402: RYPLTFGW (HIV nef), HLA-B*2705: TSTLQEQIGW (HIV gag).
cEffect observed when aa introduced in KIR3DL1*015.
dEffect observed when aa introduced in KIR3DL1*012.

**ROLE OF THE KIR3DS1 IN DISEASES**

Several studies have identified KIR3DS1 to be associated with the outcome of various diseases (reviewed in Jamil and Khakoo, 2011), including viral infections, most prominently HIV-1 infection, certain malignancies, and auto immune diseases (see Table 2). In particular, the role of KIR3DS1 in viral infections has been well-accepted since the first descriptions of significant associations between the KIR3DL1/S1 gene locus and the outcome of HIV-1 infection.
infection (Martin et al., 2002, 2007b). Subsequent studies observed a protective role of KIRDS1 in these particular cohorts (Boulet et al., 2008; Tomescu et al., 2011). In contrast, two studies conducted by Tomescu et al. (2010) and O’Connell et al. (2009) did not observe an enrichment of KIRDS1 and HLA-Bw4-I80 alleles in HESN (Tomescu et al., 2010). This suggests that host factors other than KIRDS1 may be involved in the control of HIV-1 infection.

Nevertheless, functional studies in KIRDS1+ NK cells, in particular in acute HIV-1 infection, have provided some indications for an interaction of KIRDS1 and HLA-Bw4-I80. Results obtained by Alter et al. (2009) demonstrated an expansion of KIRDS1+ NK cells in acute HIV-1 infection, however only in individuals that also encoded for HLA-Bw4-I80 alleles. In addition, HLA-Bw4-I80-dependent killing of HIV-1 infected target cells and inhibition of viral replication by KIRDS1+ NK cells has been described (Alter et al., 2007). Although a subsequent study conducted by Leng et al. (2008) observed increased IFN-γ and CD107a expression of NK cells in KIRDS1+ individuals with early HIV-1 infection, this finding was independent of the joint carriage of HLA-Bw4-I80. However, the authors did observe higher IFN-γ and CD107a expression in individuals encoding for both KIRDS1 and HLA-Bw4 alleles, in particular in the presence of the B*58 alleles, and the lack of detecting a statistical significance for higher NK cell activity in KIRDS1+ HLA-Bw4-I80+ individuals might have been a consequence of the small sample size. In addition, increased frequency and antiviral capacity against HIV-1 of KIRDS1+ NK cells were recently described in individuals encoding for multiple copies of KIRDL1 (Pelak et al., 2011). The results from the study by Pelak et al. (2011) indicate that KIRDL1-dependent licensing of NK cells might be involved in shaping a strong antiviral response of KIRDS1+ NK cells. Higher responsiveness of licensed NK cells might therefore serve as one potential underlying mechanism for the protective effect of the combined presence of KIRDS1 and its cognate HLA ligands in chronic HIV-1 infection (Kim et al., 2008).

Overall, although a beneficial effect of KIRDS1 in the context of HIV-1 infection has been observed in some in vivo and in vitro, it remains unknown whether this effect is mediated by KIRDS1 itself or other genes in linkage disequilibrium with KIRDS1. Furthermore, it is not clear whether changes in KIRDS1 copy numbers in KIRDS1+ individuals are responsible for this protective effect or whether this is dependent on the simultaneous presence of HLA-Bw4-I80.

The role of KIRDS1 has also been investigated in other viral infections such as human T-cell leukemia virus type 1 (HTLV-1), H1N1 influenza A, and hepatitis B virus infection (HBV). While no evidence for the participation of KIRDS1 in control of HTLV-1 infection was found (O’Connor et al., 2012), carriage of KIRDS1 and other haplotype B containing KIRs was associated with severe pandemic influenza A (H1N1) 2009 infections (Aranda-Romo et al., 2011). Frequencies of KIRDS1 as well as KIRDS1 and KIR2DL5 were furthermore increased in a group of patients who spontaneously recovered from HBV compared to individuals with chronic HBV infection or healthy controls (Zhi-Ming et al., 2007). Because of the close proximity of the genes within the KIR locus and the resulting strong linkage disequilibrium with neighboring genes, it remains unclear whether the observed effects are due to a specific KIR. Furthermore, the mechanisms underlying a

### Table 2 | Selected disease associations of KIRDS1

| Disease                          | Association when KIRDS1 is present                                                                 |
|----------------------------------|-----------------------------------------------------------------------------------------------------|
| **Viral infections**             |                                                                                                     |
| HIV-1                            | Delayed progression to AIDS in combination with HLA-Bw4-I80 (Martin et al., 2002)                   |
| Hepatitis B virus infection      | Increased rate of spontaneous recovery (Zhi-Ming et al., 2007)                                       |
| H1N1 influenza-A                 | Severe pandemic influenza A infections (Aranda-Romo et al., 2011)                                     |
| **Malignancies**                 |                                                                                                     |
| Hepatocellular carcinoma         | Reduced risk in combination with HLA-Bw4-I80 (Lopez-Vazquez et al., 2009)                            |
| Hodgkin’s lymphoma               | Reduced risk (Besson et al., 2007)                                                                   |
| Respiratory papillomatosis       | Reduced risk (Bonavida et al., 2009)                                                                 |
| Cervical neoplasia               | Increased risk (Carrington et al., 2005)                                                            |
| **Other**                        |                                                                                                     |
| Allogeneic HSCT                  | Decreased progression-free survival of patients with multiple myeloma (Kondel et al., 2010); decreased overall survival in HLA-Bw4+ patients (Guine et al., 2008); decreased acute GVHD (Klein et al., 2010) |
| Ankylosing spondylitis (AS)      | Increased susceptibility for development of AS (Lopez-Larrea et al., 2006; Diaz-Pena et al., 2008)     |
potential protective effect of specific KIR genotypes remain to be elucidated.

A side from their important role in controlling viral infections, NK cells can also mediate antitumor immunity (reviewed in Wu and Lanier, 2003). Association studies investigating the impact of KIR/HLA haplotypes in selected malignancies have identified protective as well as unfavorable KIR/HLA haplotypes, including some comprising KIR3DS1 (Arnheim et al., 2005; Purdy and Campbell, 2009; Karabon et al., 2011). A protective effect of KIR3DS1 in combination with HLA class I molecules expressing the HLA-Bw4-II8 epitope in hepatocellular carcinoma has been observed in patients with chronic HCV infection (Lopez-Vazquez et al., 2005). The underlying mechanism of this protective genotype is not known. It is possible that transformed cells in the HCV-infected liver encode for a KIR3DS1 ligand and are directly recognized and killed by KIR3DS1+ NK cells. A decreased risk for the development of Hodgkin's lymphoma (HL), a common lymphoma in young adults, was also identified in individuals carrying KIR3DS1 in familial study with 90 cases and 255 first-degree relatives (Besson et al., 2007). In addition, absence of KIR3DS1 and KIR2DS1, which display strong linkage disequilibrium, was associated with more frequent occurrence of respiratory papillomatosis (RRP), a rare disease of the larynx and upper airway caused by human papillomaviruses (HPV)-6/11 (Bonagura et al., 2010). Of note, all three malignancies described above are caused at least promoted by viral infections, indicating a potential role of KIR3DS1 in the control of the underlying viral infections.

Thus, it is possible that the protective role of KIR3DS1 is due to the recognition of virus-infected cells by KIR3DS1+ NK cells similar to other viral infections. In contrast, some studies have described a detrimental effect of KIR3DS1 in cervical cancer and on the outcome of unrelated hematopoietic stem cell transplantation (HSCT). An increased susceptibility to the development of cervical neoplasia in patients carrying KIR3DS1 was identified by Carrington et al. (2005). Of note, similar to the above mentioned RRP, cervical neoplasia is also a HPV-associated disease. However, in this case the presence of KIR3DS1+ NK cells might be detrimental due to incomplete viral control and chronic inflammation that might facilitate the development of cancer.

In a multivariante analysis Gabriel et al. (2010) showed that progression-free survival of patients with multiple myeloma after autologous stem cell transplantation was significantly decreased in patients carrying the KIR3DS1 gene. Furthermore, Gagne et al. (2009) observed the lowest overall survival in HLA-Bw4+ patients with myelogenous diseases receiving KIR3DL1+/KIR3DS1+ donor NK cells during HSCT. In contrast, a beneficial effect of KIR3DS1 in the context of T cell-depleted HSCT has also been observed, showing a protective effect of donor KIR haplotype B against leukemic relapse and improved disease-free survival in patients undergoing HSCT (Verheyden et al., 2005; Marcenares et al., 2011). Veenstrom et al. (2010) furthermore showed that transplantation of hematopoietic stem cells from KIR3DS1+ donors was associated with decreased acute graft-versus-host disease (GVHD). Although the underlying mechanism of the observed effects are not understood, the above studies indicate a potential role of NK cell licensing in the setting of HSCT as the HLA and KIR haplotypes of the donor define NK cell responses in the new host.

Finally, with regards to autoimmune diseases, a growing number of studies suggest a role for NK cells in disease pathogenesis. In particular, KIR3DS1 has been associated with the development and progression of ankylosing spondylitis (AS; reviewed in Diaz-Pena et al., 2009 and Aruz-Lieberman et al., 2005). AS represents a prototypic subtype of a group of various related diseases summarized as spondyloarthritides (reviewed in Dougados and Biererin, 2011). The characteristic symptoms include chronic inflammation of the joints and ligaments of the spinal bones that can be triggered by mechanical or bacterial stress. Although the exact underlying pathology remains unknown, genetic predisposition accounts for 80–90% of the cases, and include the presence of HLA-B27 alleles as a major risk factor (Thomas and Brown, 2010). Several studies observed enrichment for KIR3DS1 in HLA-B27+ patients with AS (Lopez-Larrea et al., 2006; Diaz-Pena et al., 2010), while KIR3DL1 was found to be underrepresented in patients with AS as compared to HLA-B27+ healthy controls (Mousavi et al., 2010; Wang et al., 2012). With regards to the ligand specificity of KIR3DS1, functional studies investigating a potential interaction of KIR3DS1 and HLA-B27 in the context of AS have not been conducted. Moreover, whether the underlying mechanism of the increased susceptibility to the development of AS in KIR3DS1+ individuals involves a differential activation threshold of KIR3DS1+ NK or CD8+ T cells is not known. These data also indicate that the presence of KIR3DS1 is a more important factor in the development of AS than the absence of protective KIR3DL1 alleles. However, it should be noted that other studies neither observed any significant involvement of KIR3DS1 in the outcome of AS (Harvey et al., 2009), nor identified other compound KIR genes and HLA alleles linked to the development and progression of AS (Diaz-Pena et al., 2008; Jiao et al., 2010; Taik et al., 2011).

Taken together, these studies suggest that KIR3DS1 might not only play a role in the outcome of viral infections, but also in malignancies, the outcome after HSCT, and auto immune disease. Additional functional studies of NK cells are required in these disease settings to determine whether KIR3DS1 exerts its protective or detrimental effects through modulation of NK cell function, or by alternative mechanisms.

CONCLUDING REMARKS

An accumulating number of studies have demonstrated the influence of KIR3DS1 on the outcome of various human diseases. Furthermore, the ubiquitous presence of KIR3DS1 within human populations suggests an evolutionary pressure to maintain this activating KIR. The lack of a defined ligand for KIR3DS1 has significantly hampered functional studies to determine the mechanism underlying KIR3DS1-associated protection from disease, but might also suggest a restricted engagement of KIR3DS1 to prevent killing of normal cells and thus damage of the host.

ACKNOWLEDGMENTS

This study was supported by the NIH (R01 AI066031), the Doris Duke Charitable Foundation, and the Ragon Institute of MGH, MIT and Harvard. We thank Cormac Cosgrove and Sagar A. Vaidya for critical review of this manuscript.

www.frontiersin.org November 2012 | Volume 3 | Article 326 | 7
REFERENCES

Abi-Rached, L., and Parham, P. (2005). Natural selection drives recurrent formation of activating killer cell immunoglobulin-like receptors and Ly49 from inhibitory homologues. J. Exp. Med. 199, 1139–1152.

Albrecht, G., Martin, M. P., Tjernberg, L., Carr, W. H., Svejgaard, T., J. S. Schneider, A., et al. (2007). Differential natural killer cell-mediated inhibition of HIV-1 replication based on distinct KIR/HLA subtypes. J. Exp. Med. 204, 3027–3036.

Albrecht, G., Bühn, S., Wagner, N., Neit, A., Martin, M. P., Rosenberg, E. B., et al. (2009). HLA class I subtypes dependent expansion of KIR3DS1 and KIR3DL1 NC cells during acute human immunodeficiency virus type 1 infection. J. Virol. 83, 6794–6805.

Aramendi, S., Garcia-Sepulveda, C. A., Comas-Garcia, A., Ibarra-Salinas, F., Jalgado-Bustamante, M., Grompe-Gomez, A., et al. (2012). Killer cell immunoglobulin-like receptor genes in severe A (HIN1) 2009 influenza infections. J. Immunogenet. 39, 653–662.

Armstrong, L., Dillen, J., and Sanjuro, C. B. (2005). A population-based cohort study of KIR genes and genotype in relation to cervical intragrainful neoplasia. Tissue Antigens 65, 252–274.

Armstrong, N., Markel, G., Mirahmadi, S., Garetz, R., Harma, J., Asharot, H., et al. (2005). The involvement of NC cells in killing spindylitis. Int. J. Immunogenet. 17, 857–860.

Barbour, J. D., Strain, U., Callier, S. I., Lee, J. A., Hefel, F. M., and Okambara, J. R. (2007). Synergy or independence? Deciphering the interaction of HLA Class I and NC cell KIR ligands in early HIV disease progression. PLoS Pathog. 3, e34. doi: 10.1371/journal.ppat.0020034

Bassou, C., Boynynek, S., Williams, F., Orsi, L., Amlé, C., Lepesden, V., et al. (2007). Association of killer cell immunoglobulin-like receptor genes with Hodgkin’s lymphoma in a familial study. PLoS ONE 2, e486. doi: 10.1371/journal.pone.0000849

Bassou-B, Falco, S., Cambiaggi, A., W. H., Suscovich, T. J., Schneidewind, A., Achdout, H., et al. (2005). The involvement of NC cells in killing spindylitis. Int. J. Immunogenet. 17, 857–860.

Bassou, C., Boynynek, S., Williams, F., Orsi, L., Amlé, C., Lepesden, V., et al. (2007). Association of killer cell immunoglobulin-like receptor genes with Hodgkin’s lymphoma in a familial study. PLoS ONE 2, e486. doi: 10.1371/journal.pone.0000849

Bassou-B, Falco, S., Cambiaggi, A., W. H., Suscovich, T. J., Schneidewind, A., Achdout, H., et al. (2005). The involvement of NC cells in killing spindylitis. Int. J. Immunogenet. 17, 857–860.

Bassou, C., Boynynek, S., Williams, F., Orsi, L., Amlé, C., Lepesden, V., et al. (2007). Association of killer cell immunoglobulin-like receptor genes with Hodgkin’s lymphoma in a familial study. PLoS ONE 2, e486. doi: 10.1371/journal.pone.0000849

Bassou-B, Falco, S., Cambiaggi, A., W. H., Suscovich, T. J., Schneidewind, A., Achdout, H., et al. (2005). The involvement of NC cells in killing spindylitis. Int. J. Immunogenet. 17, 857–860.

Bassou, C., Boynynek, S., Williams, F., Orsi, L., Amlé, C., Lepesden, V., et al. (2007). Association of killer cell immunoglobulin-like receptor genes with Hodgkin’s lymphoma in a familial study. PLoS ONE 2, e486. doi: 10.1371/journal.pone.0000849

Bassou-B, Falco, S., Cambiaggi, A., W. H., Suscovich, T. J., Schneidewind, A., Achdout, H., et al. (2005). The involvement of NC cells in killing spindylitis. Int. J. Immunogenet. 17, 857–860.

Bassou, C., Boynynek, S., Williams, F., Orsi, L., Amlé, C., Lepesden, V., et al. (2007). Association of killer cell immunoglobulin-like receptor genes with Hodgkin’s lymphoma in a familial study. PLoS ONE 2, e486. doi: 10.1371/journal.pone.0000849

Bassou-B, Falco, S., Cambiaggi, A., W. H., Suscovich, T. J., Schneidewind, A., Achdout, H., et al. (2005). The involvement of NC cells in killing spindylitis. Int. J. Immunogenet. 17, 857–860.

Bassou, C., Boynynek, S., Williams, F., Orsi, L., Amlé, C., Lepesden, V., et al. (2007). Association of killer cell immunoglobulin-like receptor genes with Hodgkin’s lymphoma in a familial study. PLoS ONE 2, e486. doi: 10.1371/journal.pone.0000849

Bassou-B, Falco, S., Cambiaggi, A., W. H., Suscovich, T. J., Schneidewind, A., Achdout, H., et al. (2005). The involvement of NC cells in killing spindylitis. Int. J. Immunogenet. 17, 857–860.

Bassou, C., Boynynek, S., Williams, F., Orsi, L., Amlé, C., Lepesden, V., et al. (2007). Association of killer cell immunoglobulin-like receptor genes with Hodgkin’s lymphoma in a familial study. PLoS ONE 2, e486. doi: 10.1371/journal.pone.0000849

Bassou-B, Falco, S., Cambiaggi, A., W. H., Suscovich, T. J., Schneidewind, A., Achdout, H., et al. (2005). The involvement of NC cells in killing spindylitis. Int. J. Immunogenet. 17, 857–860.

Bassou-B, Falco, S., Cambiaggi, A., W. H., Suscovich, T. J., Schneidewind, A., Achdout, H., et al. (2005). The involvement of NC cells in killing spindylitis. Int. J. Immunogenet. 17, 857–860.
(2010). Polymorphisms of KIR gene and HLA-C: allotypic possible association with susceptibility to HLA-B7-positive patients with ankylosing spondylitis. J Clin Immunol 30, 840–844.

Kabaoun, L., Jedynak, A., Giebel, R., Shi, J., Song, J., Xiong, A., et al. (2008). Association of the KIR3DL1 subtypes against the development of hepatitis B carcinoma in patients with hepatitis C virus infection. J Infect Dis 197, 162–175.

Kamau, K., Jei, T., Nakayama, T., Wier, J. R., Gao, C. F., Maenaka, T., et al. (1999). Killer cell immunoglobulin-like receptor receptors and T cell receptors bind peptide-major histocompatibility complex class I with distinct thermodynamic and kinetic properties. J Biol Chem. 274, 28293–28294.

Kalluri, R., Cheresh, D. A., Norman, P. J., Jourdan, M., Yawata, N., Gleimer, M., and Parham, P. (2008). Synergistic poly- 

merization at two positions distal to the ligand-binding site makes KIR3DL1 a stronger receptor for HLA-C than KIR3DS1. J Immunol. 180, 3960–3967.

Kooistra, A., Vidal, M., Hotton, C., Onesto, A. M., Mortelli, L., Avgiagelis, B. R., et al. (1997). PSMB3 as putative receptors for major histocompatibility complex (MHC) class I molecules in human natural killer (NK) cells. Anti-IGB nucleoside resistance of MHC class I-protected cells in NK clones displaying different specificities. J Exp Med. 178, 597–606.

Kornelius, S., Winkel, G., Schölle, V., Peroni, A., Gaggs, K., Willem, C., et al. (2008). Autoantigens and allo-
geneic HLA-B44-restricted human T cells displaying different specificities. J Exp Med. 197, 1577–1588.

Kooistra, A., Vidal, M., Hotton, C., Onesto, A. M., Mortelli, L., Avgiagelis, B. R., et al. (1997). PSMB3 as putative receptors for major histocompatibility complex (MHC) class I molecules in human natural killer (NK) cells. Anti-IGB nucleoside resistance of MHC class I-protected cells in NK clones displaying different specificities. J Exp Med. 178, 597–606.

Kornelius, S., Winkel, G., Schölle, V., Peroni, A., Gaggs, K., Willem, C., et al. (2008). Autoantigens and allo-
geneic HLA-B44-restricted human T cells displaying different specificities. J Exp Med. 197, 1577–1588.

Kooistra, A., Vidal, M., Hotton, C., Onesto, A. M., Mortelli, L., Avgiagelis, B. R., et al. (1997). PSMB3 as putative receptors for major histocompatibility complex (MHC) class I molecules in human natural killer (NK) cells. Anti-IGB nucleoside resistance of MHC class I-protected cells in NK clones displaying different specificities. J Exp Med. 178, 597–606.

Kornelius, S., Winkel, G., Schölle, V., Peroni, A., Gaggs, K., Willem, C., et al. (2008). Autoantigens and allo-
geneic HLA-B44-restricted human T cells displaying different specificities. J Exp Med. 197, 1577–1588.

Kooistra, A., Vidal, M., Hotton, C., Onesto, A. M., Mortelli, L., Avgiagelis, B. R., et al. (1997). PSMB3 as putative receptors for major histocompatibility complex (MHC) class I molecules in human natural killer (NK) cells. Anti-IGB nucleoside resistance of MHC class I-protected cells in NK clones displaying different specificities. J Exp Med. 178, 597–606.

Kornelius, S., Winkel, G., Schölle, V., Peroni, A., Gaggs, K., Willem, C., et al. (2008). Autoantigens and allo-
geneic HLA-B44-restricted human T cells displaying different specificities. J Exp Med. 197, 1577–1588.

Kooistra, A., Vidal, M., Hotton, C., Onesto, A. M., Mortelli, L., Avgiagelis, B. R., et al. (1997). PSMB3 as putative receptors for major histocompatibility complex (MHC) class I molecules in human natural killer (NK) cells. Anti-IGB nucleoside resistance of MHC class I-protected cells in NK clones displaying different specificities. J Exp Med. 178, 597–606.

Kornelius, S., Winkel, G., Schölle, V., Peroni, A., Gaggs, K., Willem, C., et al. (2008). Autoantigens and allo-
geneic HLA-B44-restricted human T cells displaying different specificities. J Exp Med. 197, 1577–1588.

Kooistra, A., Vidal, M., Hotton, C., Onesto, A. M., Mortelli, L., Avgiagelis, B. R., et al. (1997). PSMB3 as putative receptors for major histocompatibility complex (MHC) class I molecules in human natural killer (NK) cells. Anti-IGB nucleoside resistance of MHC class I-protected cells in NK clones displaying different specificities. J Exp Med. 178, 597–606.

Kornelius, S., Winkel, G., Schölle, V., Peroni, A., Gaggs, K., Willem, C., et al. (2008). Autoantigens and allo-
geneic HLA-B44-restricted human T cells displaying different specificities. J Exp Med. 197, 1577–1588.

Kooistra, A., Vidal, M., Hotton, C., Onesto, A. M., Mortelli, L., Avgiagelis, B. R., et al. (1997). PSMB3 as putative receptors for major histocompatibility complex (MHC) class I molecules in human natural killer (NK) cells. Anti-IGB nucleoside resistance of MHC class I-protected cells in NK clones displaying different specificities. J Exp Med. 178, 597–606.

Kornelius, S., Winkel, G., Schölle, V., Peroni, A., Gaggs, K., Willem, C., et al. (2008). Autoantigens and allo-
geneic HLA-B44-restricted human T cells displaying different specificities. J Exp Med. 197, 1577–1588.

Kooistra, A., Vidal, M., Hotton, C., Onesto, A. M., Mortelli, L., Avgiagelis, B. R., et al. (1997). PSMB3 as putative receptors for major histocompatibility complex (MHC) class I molecules in human natural killer (NK) cells. Anti-IGB nucleoside resistance of MHC class I-protected cells in NK clones displaying different specificities. J Exp Med. 178, 597–606.
Pando, M. J., Gardiner, C. M., Pascal, V., Yamada, E., Martin, M. P., O'Connor, G. M., Yamada, E., Ram-Qi, Y., Martin, M. P., Gao, X., Pelak, K., Need, A. C., Fellay, J., Shirali, P., Rajagopalan, S., and Long, E. O. (2005). Phenotypic analysis of HIV-1 infected cells expressing KIR3DS1 and KIR3DL1 using the Z27 transposon. J. Immunol. 175, 2311–2317.

Varinon, J., Kaur, T., Doherty, J. M., and Square, D. (2005). Structural and functional differences between the promoters of independently expressed killer cell Ig-like receptors. J. Biol. Chem. 280, 4791–4800.

Van der Horst, S., Verheyden, S., Oostra, B. A., van Leeuwen, E. W., van der Veen, Y., van den Broek, N., and Ramos, E. (2005). Novel KIR alleles and their expression levels on NK cells: convergent evolution of KIR3DS1 phenotype variation? J. Immunol. 175, 997–1005.

Vyas, P., Ronco, A., King, J. L., and Long, E. O. (2004). Natural killer cell signal-regulating pathway. Science 305, 1517–1519.

Wang, S., Lu, G., Gu, R., Duan, Z., Zeng, Z., Zhang, T., et al. (2002). Association of KIR genotype with susceptibility to HIV-1 infection. Nature 420, 552–555.

Weidenbach, K., Corliss, B., et al. (2010). Mechanisms of copy number variation and hybrid generation of peptide-MHC class I complexes. Hum. Mol. Genet. 19, 785–791.

Wells, J. G., Bashirova, A., Norman, P. J., Yamada, N., O'Connor, G. M., Bashirova, A., and Long, E. O. (2004). KIR3DL1. Immunity 72, 148–159.

Wilson, M. J., Torkar, M., Haude, A., Sutter, D., Milteny, M., and Uhrberg, M. (2008). Lineage-specific transition of homeostatic killer cell Ig-like receptor locus from hematopoietic progenitor to NK cells. J. Immunol. 180, 418–423.

Winters, G. R. J., Miller, J. S., and Andrews, T. J. (2003). Different and divergent 5' regulatory distal KIR promoters and transcripts. Proc. Natl. Acad. Sci. U.S.A. 100, 15236–15241.

Witek, C., Nunes, J. A., and Voly, E. (2004). Natural killer cell signaling pathways. Science 305, 1517–1519.

Wright, C. A., van Bergen, J., and Trowsdale, J. (2005). Structural and functional differences between the promoters of independently expressed killer cell Ig-like receptors. J. Biol. Chem. 280, 4791–4800.

Xie, X., Martin, M. P., Gao, X., Jacobson, L., Goulet, J. L., Buschbinder, S., et al. (2006). KIR/HLA phenotypic protection against both HIV and opportunistic infections. Proc. Natl. Acad. Sci. U.S.A. 103, 15236–15241.

Zhang, Y., Yang, H., Li, G., Ge, R., Duan, Z., Zeng, Z., et al. (2006). KIR3DS1 and 3DL1 using the Z27 transposon. J. Immunol. 175, 997–1005.
cell inhibitory receptor controls the ability of natural killer cells to discriminate between the two groups of HLA-C allotypes. J. Immunol. 158, 4026–4028.

Wu, J., and Lanier, L. L. (2003). Natural killer cells and cancer. Adv. Cancer Res. 90, 127–156.

Yawata, M., Yawata, N., Draghi, M., Little, A. M., Parham, P. (2006). Roles for HLA and KIR polymorphisms in natural killer cell repertoires selection and modulation of effector function. J. Exp. Med. 205,631–645.

Zappacosta, F., Bergego, F., Brooks, A. G., Parker, K. C., and Coligan, J. E. (1997). Peptides isolated from HLA-Cw*0304 confer different degrees of protection from natural killer cell-mediated lysis. Proc. Natl. Acad. Sci. U.S.A. 94, 6315–6318.

Zhi-Ming, L., Yu-Lian, J., Zhao-Lei, F., Chun-Xiao, W., Zhen-Fang, D., Bing-Chang, Z., et al. (2007). Polymorphisms of killer cell immunoglobulin-like receptor gene: possible association with susceptibility to or clearance of hepatitis B virus infection in Chinese Han population. Croat. Med. J. 48, 800–806.

**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received: 12 June 2012; accepted: 09 October 2012; published online: 01 November 2012.

Citation: Körner C and Altfeld M (2012) Role of KIR3DS1 in human diseases. Front. Immunol. 3:326. doi: 10.3389/fimmu.2012.00326

This article was submitted to Frontiers in NK Cell Biology, a specialty of Frontiers in Immunology. Copyright © 2012 Körner and Altfeld. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in other forums, provided the original authors and source are credited and subject to any copyright notices concerning any third-party graphics etc.