



Perturbation of mucosal-associated invariant T cells and iNKT cells in HIV infection

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Purpose of review

To analyze the possible role that the 'unconventional' T-cell populations mucosal-associated invariant T cell (MAIT) and iNKT cells play during HIV infection and following antiretroviral therapy (ART) treatment.

Recent findings

A substantial body of evidence now demonstrates that both MAIT and iNKT cells are depleted in blood during HIV infection. The depletion and dysfunction of MAIT and iNKT cells are only partially restored by suppressive ART, potentially contributing to HIV-related comorbidities.

Summary

The deficiency and dysfunction of MAIT and iNKT T-cell subsets likely impact on immunity to important coinfections including *Mycobacterium tuberculosis*. This underscores the importance of research on restoring these unconventional T cells during HIV infection. Future studies in this field should address the challenge of studying tissue-resident cells, particularly in the gut, and better defining the determinants of MAIT/iNKT cell dysfunction. Such studies could have a significant impact on improving the immune function of HIV-infected individuals.

Keywords

antiretroviral therapy, iNKT, mucosal-associated invariant T cell, mucosa, unconventional T cell

INTRODUCTION

Unconventional T cells, restricted by nonclassical major histocompatibility (MHC) proteins, exhibit both the antigen specificity of classic adaptive immunity and the rapid responsiveness of the innate immune system, giving them a unique role in the immune response to viral and microbial pathogens [1]. In humans, unconventional T cells tend to share the expression of CD161 (NKR-P1A) [2], and of the CD161-expressing lymphocytes, iNKT cells and mucosal-associated invariant T cells (MAIT) have a clearly restricted T-cell antigen receptor (TCR) repertoire. iNKT cells are more abundant than MAIT cells in mice, whereas MAIT cells are more numerous in humans, comprising up to 15% of circulating CD8⁺ T cells. iNKT cells are selected and develop their innate-like phenotype and function in the thymus prior to egress. They also express the transcription factor ZBTB16 (PLZF), which is crucial for their innate/effector functions [3,4]. In contrast, MAIT cells are naive and low in frequency in the thymus, and only low amounts of the TCR V α 7.2-J33 transcripts are found in cord blood [5–7], although phenotypically cord blood MAIT cells

share many transcriptional features with their adult counterparts [8]. The biology of these two cell types has been recently compared in detail elsewhere [9].

In the context of infection, both MAIT and iNKT cells respond via rapid expression of effector cytokines, for example tumor necrosis factor (TNF), interferon gamma (IFN- γ), interleukin 17 (IL-17) and

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Curr Opin HIV AIDS 2019, 14:77–84

DOI:10.1097/COH.0000000000000526

KEY POINTS

- Both MAIT and iNKT cells are depleted from peripheral blood during untreated HIV infection.
- ART does not fully reconstitute the frequency or function of residual iNKT/MAIT cells.
- Determinants of residual iNKT/MAIT cell dysfunction, that is ICRs, are poorly defined.
- Restoration of iNKT/MAIT cells in HIV-infected individuals may have important benefits for antiviral and antimicrobial immunity.

granulocytemacrophage colony-stimulating factor [10–14]. They also both produce the cytotoxic molecules granzyme B and perforin [15,16], which causes a sequence of events that lead to target cell death via the caspase pathway [17]. In addition to TCR-mediated activation, both MAIT and iNKT cells can be activated in a TCR-independent manner relying on cytokine stimulation (typically IL-12, IL-18 and/or IL-15) [18–21]. Modulation of MAIT or iNKT cells during HIV infection could potentially have impacts on host defense against bacteria, yeasts and viruses [20,21]. In this review, we summarize the current understanding of the impact of HIV infection on MAIT and iNKT T-cell subsets (summarized in Table 1) [22–27,28[■], 29–33,34[■],35–38] and highlight the translational potential of these cells in HIV treatment, prevention and cure approaches.

MUCOSAL-ASSOCIATED INVARIANT T CELLS

Mucosal-associated invariant T cells (MAIT cells) are innate-like T cells that express a semi-invariant TCR and rapidly produce cytokines upon activation [39]. Expression of the V α 7.2 TCR (rearranged typically with J α 33), restriction by the evolutionary conserved nonpolymorphic MHC-related protein MR1, as well as the expression of the C-type lectin

CD161⁺⁺ and IL18R, help define human MAIT cells. MR1 presents vitamin B metabolites produced by some but not all bacteria and fungi. The most potent riboflavin (vitamin B2) antigens for MAIT cell activation and development are 5-OP-RU and 5-OE-RU [40–42]. Human MAIT cells typically express either CD8 $\alpha\beta$ or CD8 $\alpha\alpha$ dimers, but can occasionally exhibit a CD4/CD8 double negative (DN) phenotype or, rarely, be CD4⁺. MAIT cells share key differentiation factors with Th17 cells, which include: transcription factors (ROR γ t and RUNX2), cytokine expression (IL17A and IL22), chemokine receptors (CCR6 and CCR2) and cytokine receptors (IL23R and IL18R).

Mucosal-associated invariant T cells in untreated HIV infection

Although MAIT cells were initially studied for their responses to bacterial infection, their role in viral infections has also recently been investigated [12,43]. Depletion of MAIT cells in blood of patients with chronic viral infections, such as HBV, HCV and HIV, is common. Dramatic early and nonreversible loss of CD161⁺⁺/MAIT cell numbers has been particularly observed in HIV infection [22,23]. This loss is further confirmed in simian immunodeficiency virus (SIV) infection in rhesus macaques [24]. Low frequencies of MAIT cells were observed in peripheral blood, mesenteric lymph nodes and broncho-alveolar lavage fluid of SIV-infected macaques. Decreases of MAIT cells were coupled with increased proliferation and a highly public TCR repertoire, although without redistribution to other anatomical sites. Systemic decrease of MAIT cells may be attributed to enhanced turnover in SIV infection that may cause impairment of protection against certain opportunistic infections including *M. tuberculosis* infection.

There are several possible explanations as to why MAIT cells are depleted during HIV infection. The apparent loss of MAIT cells in blood could potentially be due to down regulation of CD161 expression leading to an underestimation of CD161^{hi}V α 7.2⁺

Table 1. Summary of alterations of mucosal-associated invariant T cell and iNKT cell during treated and untreated HIV infection

T-cell subset	Characteristic	Untreated HIV infection	ART-treated HIV infection	References
MAIT cells	Frequency (peripheral blood)	Depleted	Partially restored	[22–24]
	Frequency (tissue)	Depleted or unaltered	Restored	[25,26]
	Function (cytokine/proliferation)	Reduced (chronic infection only)	Partially restored	[23,26,27]
iNKT cells	Frequency (peripheral blood)	Depleted	Partially restored	[28 [■] ,29–32]
	Frequency (tissue)	Depleted or unaltered	Unaltered	[33,34 [■]]
	Function (cytokine/proliferation)	Reduced	Partially restored	[35–38]

MAIT cells. However, the use of MR1/5-OP-RU tetramers has confirmed previous findings of MAIT cell depletion [27]. The upregulation of MAIT cell tissue homing markers (CCR2⁺, CCR5⁺, CCR6⁺, CCR9⁺ and CXCR6⁺) and the detection of MAIT cells in inflamed tissues raise the possibility that MAIT cells may migrate out of the circulation and into tissues during infection [18]. This may be relevant to bacterial translocation from the gut during HIV infection and subsequent immune activation, leading to MAIT cell migration into the gut, where they are then subjected to bacteria-induced apoptosis [23].

The loss of MAIT cells is also evident in HIV/tuberculosis (TB) coinfection [44], and may contribute to increased susceptibility to *M. tuberculosis* infection, or to other bacterial and fungal infections [23]. Patients with HIV and concomitant HCV coinfection have even lower peripheral MAIT cell frequencies with high levels of immune activation (CD38⁺HLA-DR⁺). Higher frequencies of intrahepatic MAIT cells compared to peripheral blood were observed regardless of viral infection status, but these frequencies were still lower than that found in uninfected controls [45,46]. This suggests that the low frequency of MAIT cells observed in HIV/HCV coinfection is not solely because of migration to inflamed sites, but also because of depletion at the site of infection [47]. Deletion of MAIT cells during infection may result in impairment of mucosal immunity and may contribute to the well-described reduction of barrier function in HIV disease [25].

Mucosal-associated invariant T cells in the age of antiretroviral therapy

Impairment of MAIT cell function in antiretroviral therapy (ART)-naive individuals chronically infected with HIV (~6–8 years) has been observed [25,48]. Impairment of IFN- γ and IL-17A cytokine secretion by MAIT cells upon *Escherichia coli* stimulation is partially restored with ART, although TNF production and CD69 expression were not restored with therapy. In untreated acute infection (median, 4 months), residual MAIT cells were found to be functionally active and may be able to assist in controlling bacterial infection during HIV infection [27]. IL-17A production was partially restored after 5 years of ART, whereas treatment for 2 years was not able to restore IL-17A production [23], indicative of a very slow recovery of MAIT cell function following therapy. Taken together, while depletion of MAIT cells occurs early, functional impairment may develop later during established HIV infection: treatment may partially and slowly restore MAIT cell function in chronic patients [26]. Early diagnosis and early treatment may be vital to improve functionality during HIV infection.

Expression of immune checkpoint receptors (ICRs) has been implicated in many disease settings to confer immune activation/inhibition that leads to exhaustion. Programmed cell death protein 1 (PD-1) has been shown to be highly expressed on MAIT cells in peripheral blood of HIV-infected and HIV/TB coinfecting individuals. TIM-3 expression was also elevated on MAIT cells in chronic HIV infection compared to uninfected controls. Treatment with ART was able to significantly lower TIM-3 levels but not PD-1 levels on MAIT cells [25]. Expression of other ICRs, such as LAG-3, CD244, CTLA-4 and TIGIT, is yet to be investigated on MAIT cells in different stages of HIV infection. Whether the high expression of ICRs correlates with impaired function of MAIT cells is to be determined.

IL-7 is a pleiotropic cytokine that has many functions [49], which include acting as a growth factor for gut mucosal lymphocytes, conferring strong survival signals for homeostatic proliferation of memory T cells and enhancing Th1 and Th17 cytokine production. IL-7 has been shown to activate resting MAIT cells from healthy donors to become cytotoxic granzyme B expressing effector cells [50]. IL-7 plasma levels positively correlate with higher MAIT cell frequencies and improve function in HIV-infected patients. IL-7 treatment significantly restored MAIT cell effector function *in vitro*, even when ART was not administered [51[■]]. Thus, the immunotherapeutic properties of IL-7 together with ART should further be explored to harness the protective function of MAIT cells in HIV disease.

Future directions: mucosal-associated invariant T cells and HIV prevention

It is now clear that MAIT cells have the ability to sense viral infections through specific cytokine-driven mechanisms. There is a general decrease in MAIT cell frequencies during several chronic viral infections, although these observations were mostly made on peripheral blood. Much work remains to be done to understand the role of MAIT cells during HIV infection. There is a strong need to characterize the MAIT cells from different mucosal tissue compartments, particularly the gut-associated lymphoid tissue (GALT) of HIV-infected individuals. Additional cohorts of elite controllers, viremic controllers, TB-HIV coinfection and HCV-HIV coinfection should be carefully studied. Gastric MAIT cells have to been shown to express tissue-resident markers CD69 and CD103, and can rapidly respond to *Helicobacter pylori* infection [52]. It remains to be seen if MAIT cells in tissue compartments of HIV-infected individuals are able to respond to HIV infection and play a role in preventing acute infection of CD4 T

cells. Assessment of immune-senescence and cell exhaustion needs to be studied in more detail in both blood and tissue compartments, with particular emphasis on inhibitory receptors that may affect MAIT cell function. The interaction of MAIT cells with other innate and adaptive cells within tissue compartments should be investigated, as activated antigen presenting cells and other lymphocytes are sources of cytokines that can lead to MAIT activation during viral infection. Finally, to what extent MAIT cell frequencies and functions can be restored in HIV and what approaches beyond extended ART could impact on this is an important translational question. If the tissue-homing and cytotoxic potential of MAIT cells could contribute to the control of latent reservoir (as well as promoting overall host immunity), this would be a novel approach to HIV cure strategies.

INKT CELLS

iNKT cells (also known as Type I natural killer T (NKT) cells) are a CD1d-restricted T-cell subset characterized by the expression of a semi-invariant TCR ($V\alpha 24$ - $J\alpha 18$ most commonly paired with $V\beta 11$) [1]. Other NKT cell subsets, such as the more diverse group of Type II NKT cells [53], will not be considered in this review. Human iNKT cells represent approximately 0.1% of peripheral blood T cells and exhibit functional heterogeneity based on the expression of the CD4 and CD8 coreceptors [54]. iNKT cell phenotype, function and antigen specificity have recently been comprehensively reviewed [1,55].

iNKT cells in untreated HIV infection

It has been 16 years since van der Vliet *et al.* [56], Sandberg *et al.* [57] and Motsinger *et al.* [58] reported the depletion of iNKT cells in the peripheral blood of HIV-infected individuals. Since then, numerous cohort studies have confirmed their observations [28[•],59–62], and suggested that iNKT depletion occurs rapidly after acute infection [27,56,62]. Depletion is observed in both HIV-1 and HIV-2 infection [63], occurs independently of the clade of HIV-1 infecting virus [59,60] and correlates with markers of HIV disease progression in the vast majority of cohorts [57,62,63]. Although the mechanisms of iNKT loss may be multifactorial [56], the major contributing factor is the selective depletion of the $CD4^+$ iNKT subset [29,57,59,61–63]. A subset of $CD4^+$ iNKT cells express CCR5 [58], and in-vitro studies have confirmed that both resting and antigen-activated $CD4^+$ iNKT cells are highly susceptible to HIV infection [57,58,64]. Similar results have been reported during SIV infection of nonhuman primates [65,66]

with the exception of sooty mangebeys, which naturally lack $CD4^+$ iNKT cells and exhibit no iNKT depletion during nonpathogenic SIV infection [67].

Despite the importance of the GALT as a site of HIV replication and associated microbial translocation, data on mucosal iNKT cell populations during HIV infection are scarce. To date, only two studies have assessed GALT iNKT cells in infected individuals, with divergent results. Ibarrondo *et al.* [33] reported that $CD4^+$ iNKT cells, which were enriched in the GALT relative to peripheral blood mononuclear cell (PBMC), were substantially depleted in HIV-infected individuals. This depletion correlated with viral load and systemic T-cell activation, whereas peripheral $CD4^+$ iNKT depletion did not. In contrast, Paquin-Proulx *et al.* [34^{••}] observed a nonsignificant increase in the proportion of gut iNKTs that were $CD4^+$ in HIV-infected individuals, with no changes in total iNKT frequency compared to controls. In this cohort, GALT iNKT IL-10 and IL-4 production were associated with lower levels of immune activation and microbial translocation. Despite the challenging nature of identifying and collecting sufficient iNKT cells from GALT samples for analysis, more studies are needed to conclusively determine the relationship between gut dysbiosis, immune activation and iNKT responses during HIV infection.

Phenotypic and functional characterization of the residual peripheral iNKT population suggests that chronic HIV infection also leads to iNKT cell anergy or exhaustion. Multiple studies have confirmed the activated phenotype of iNKT cells during infection (as measured by CD69, CD38 and HLA-DR expression) [28[•],29,59,63] and identified defects in α GalCer- or phorbol 12-myristate 13-acetate-induced cytokine production and proliferation [35,36,62,68]. These functional deficiencies are typically attributed to the elevated expression of ICRs or differentiation markers such as PD-1 [28[•],35], LAG-3 [37], CD57 [28[•],59] and, most recently, 2B4 [61]. Despite correlations between surface phenotype and function, however, only a single study has directly demonstrated a relationship between exhaustion marker expression and lack of cytokine production on an individual cell level [37]. Furthermore, the only study to attempt to restore iNKT function *in vitro* by blocking PD-1 signaling was unsuccessful [35], leaving substantial gaps in our understanding of the mechanisms regulating iNKT exhaustion and functional capacity during HIV infection.

iNKT cells and control of HIV disease progression

The multifunctional nature of iNKT cells has led to speculation that the depletion of the $CD4^+$ subset

and compromised function of the remaining iNKT population could contribute to HIV disease progression. Data surrounding this question, however, remain speculative and circumstantial. *In vitro*, α GalCer stimulation of PBMCs can inhibit HIV replication via an IFN γ -dependent mechanism [38]. Long-term nonprogressors (LTNPs), who naturally control HIV infection, exhibit significantly higher iNKT frequencies and improved iNKT cell function

compared to normal progressors [28³⁶], but studies of LTNPs are hampered by the difficulty of determining causality between a given immune phenotype and HIV control. Perhaps, the most intriguing results in this area come from Rout *et al.* [69], who reported that in macaques, baseline iNKT cell frequencies correlated with the preservation of postinfection CD4⁺ T-cell counts, suggesting a potential impact of iNKT cells on early disease

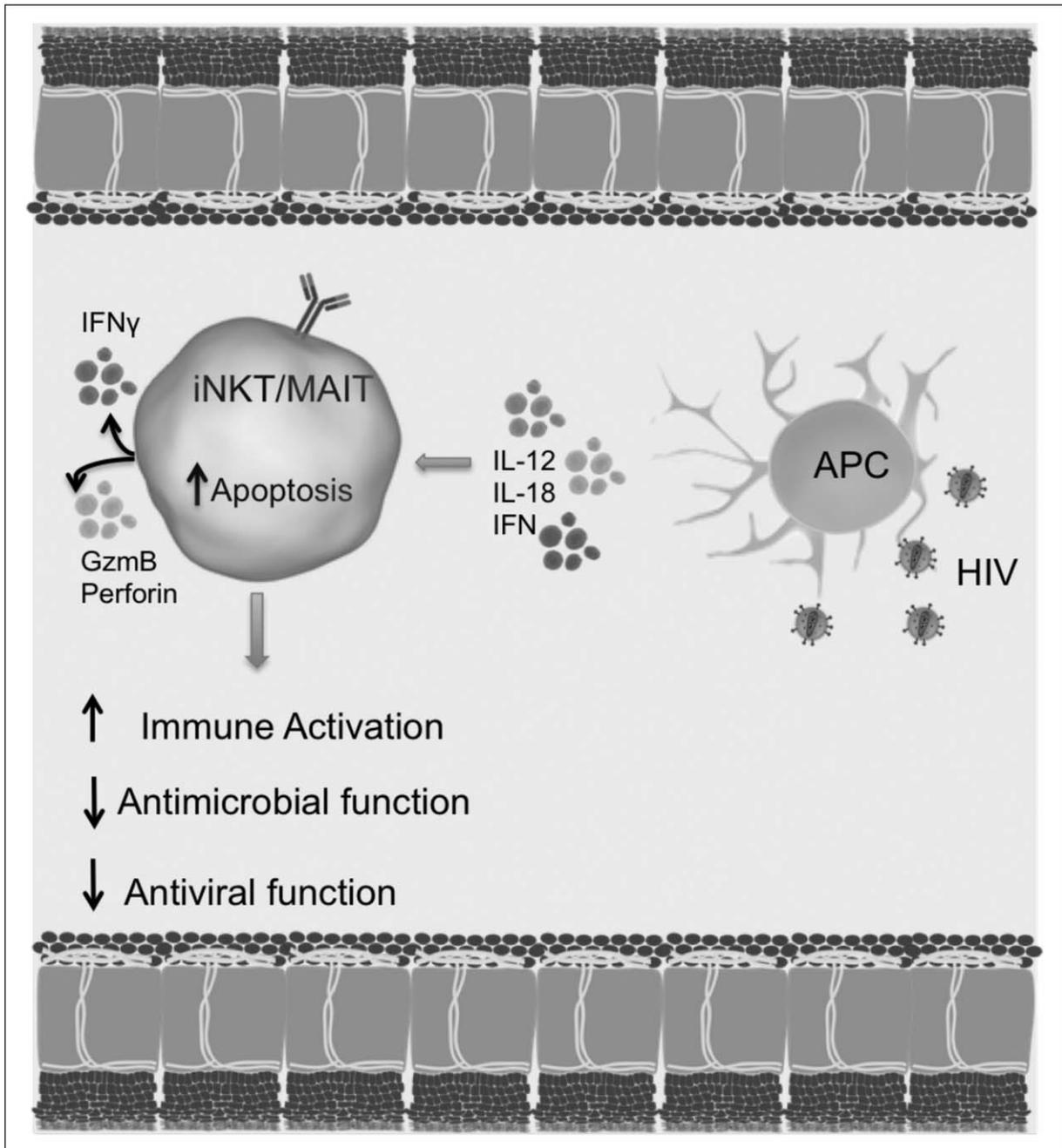


FIGURE 1. iNKT and MAIT cells in HIV infection. Virally driven cytokines produced by antigen presenting cells in blood and tissue lead to cellular activation and increase apoptosis. Overall, these events cause loss of function in iNKT and MAIT cells and reduce antimicrobial/antiviral function from these cells.

progression. Unfortunately, no additional data are available to confirm this observation, and in an interventional study of two pigtail macaques, Fernandez *et al.* [70] found no clear impact of α GalCer administration and iNKT activation on the progression of subsequent SIV infection.

iNKT cells in the age of antiretroviral therapy

The majority of data support only a partial restoration of both iNKT cell frequency and cytokine production during combination ART [28[•],29–31,37,38], although some cohorts have reported either full reconstitution of the iNKT compartment [32], or no restoration at all [35,36]. In some cases, ART restored only the CD4⁻ iNKT subset [31], whereas in other cases, results varied depending on the time of ART initiation [38] or the discrimination of individuals who did or did not achieve suppression of viremia [71]. Residual depletion and exhaustion of the iNKT compartment even during suppressive ART and conventional CD4⁺ T-cell reconstitution is consistent with data for other unconventional T-cell subsets [23,72], and suggests the potential clinical utility of immunotherapies designed to boost unconventional T-cell immunity. ART-treated individuals remain at elevated risk of coinfections, most notably *Mycobacterium tuberculosis* (Mtb) [73]. Mtb infection activates iNKT cells [74], and patients with active TB exhibit iNKT cell defects similar to those observed in HIV-infected patients [29,75]. Clinical interventions designed to reverse iNKT exhaustion or increase iNKT frequency might therefore improve TB-related immunity in HIV-infected ART-experienced populations. Immune checkpoint inhibitors have shown promise in cancer immunotherapies designed to restore anti-tumor T-cell responses [76], and might be similarly useful in restoring iNKT function during ART. Further work in this area, however, will require a more incisive effort to determine the most important determinants of iNKT dysfunction in HIV and generate proof-of-concept studies.

Future directions: iNKT cells and HIV prevention or cure

Despite the presence of both iNKT cells [77] and substantial CD1d expression in the female reproductive tract [78], the capacity of iNKT cells to limit or prevent HIV transmission is hampered by viral immune evasion strategies. Both Nef [79,80] and Vpu [77,81] interfere with the surface expression of CD1d in dendritic cells, limiting iNKT effector functions against infected cells. Alternately, iNKT cells may prove useful to HIV vaccine design. iNKT

cells can provide B cell help both *in vitro* [82] and *in vivo* [83], making α GalCer a potent adjuvant. Preliminary studies of two mucosal HIV vaccines, administered either sublingually, orally or intranasally, found that α GalCer boosted cellular immune responses [84,85] and resulted in neutralizing antibody responses at the genital mucosa [85]. α GalCer also boosted both the cellular and humoral immunogenicity of an HIV DNA vaccine [86]. All of these studies, however, were limited to mouse models, with human or nonhuman primate data lacking. Finally, iNKT cells are emerging as candidates for immunotherapy-based HIV cure strategies. As second-generation chimeric antigen receptor T (CAR-T) cells show clinical promise against multiple forms of cancer, there is a similar potential for engineered T cells to be used as anti-HIV effectors [87^{••},88]. iNKT cells may provide several benefits over traditional T cells in immunotherapy, given their potent cytotoxic function and an improved safety profile because of a lack of MHC restriction [89]. Adoptive transfer of *in vitro* expanded iNKT cells has already been tested in a human clinical trial [90[•]], and CAR-iNKT cells have shown potent antitumor activity in animal models [91]. A phase 1 trial to assess the safety of CAR-iNKT cells in neuroblastoma is currently underway (NCT03294954).

CONCLUSION

A substantial body of evidence now demonstrates that both MAIT and iNKT cells are depleted during HIV infection and only partially restored by suppressive ART. It is very likely that the combined deficiency of these unconventional T-cell subsets impacts on immunity to a variety of coinfections including *M. tuberculosis*, underscoring the value of restoring unconventional T-cell subsets in persons living with HIV (Fig. 1). Future studies in this field should address the challenge of studying tissue-resident cells, particularly in the gut, and better defining the determinants of MAIT/iNKT cell dysfunction. Such studies could have a significant impact on improving the immune function of HIV-infected individuals.

Acknowledgements

J.A.J. and S.J.K. are supported by fellowships from the NHMRC. P.K. and C.P. are supported by the Wellcome Trust (WT109965MA) an NIHR Senior Fellowship (P.K.), and the NIHR Biomedical Research Centre, Oxford.

Financial support and sponsorship

None.

Conflicts of interest

There are no conflicts of interest.

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