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Curing HIV: Seeking to Target and Clear Persistent Infection

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Human immunodeficiency virus type 1 (HIV-1) infection persists despite years of antiretroviral therapy (ART). To remove the stigma and burden of chronic infection, approaches to eradicate or cure HIV infection are desired. Attempts to augment ART with therapies that reverse viral latency, paired with immunotherapies to clear infection, have advanced into the clinic, but the field is still in its infancy. We review foundational studies and highlight new insights in HIV cure research. Together with advances in ART delivery and HIV prevention strategies, future therapies that clear HIV infection may relieve society of the affliction of the HIV pandemic.

Human immunodeficiency virus type 1 (HIV-1) has led to nearly 50 million deaths and inflicted suffering across the globe. As this pandemic emerged, a remarkable response of clinicians, researchers, social activists, the pharmaceutical industry, and public authorities resulted in the development and implementation of potent antiretroviral therapy (ART), able to arrest disease, restore health, and reduce the spread of new infection. Developments in ART continue, with long-acting antivirals and engineered antibodies in advanced clinical trials that offer the promise of replacing daily pills for treatment and prevention with only a few treatments per year (Gulick and Flexner, 2019). Sequential prime and boost vaccinations might accelerate the evolution of broadly neutralizing antibodies (bnAbs) that could reduce the incidence of new infection across the globe (Eisinger and Fauci, 2018), although recent efforts to replicate the success of RV144 (Kim et al., 2015) have recently failed with the early closure of HVTN 702 (clinicaltrials.gov NCT02968849).

Should these potential advances be effectively implemented across the globe, the effect of the HIV pandemic would be greatly reduced. However, millions will still be burdened by decades of chronic medical therapy and the stigma of HIV-1 infection, with the attendant burden on health systems worldwide. Therapy that could yield a cure or, short of viral eradication, allow durable and stringent immunological control without the need for medication (“functional cure”) would provide a transformative tool for the millions living with HIV. The major barrier to HIV cure is a population of infected, long-lived cells containing persistent and latent viral genomes that cannot be detected or eliminated by host defenses. Previous decades of study uncovered several molecular mechanisms that establish and enforce post-integration latency of this retrovirus (last reviewed in this journal in 2013; Ruelas and Greene, 2013). Ten years ago, a funding initiative was put forth by the National Institutes of Health, entitled “Martin Delaney Collaboratory: Towards an HIV-1 Cure,” which sought to bring together teams of researchers to focus on the daunting multidisciplinary task of a developing an HIV cure. Since then, numerous parallel efforts have been initiated across the world. The past decade of research has resulted in a deeper understanding of the molecular and cellular mechanisms of HIV latency, novel assays to improve our ability to measure the latent reservoir, and studies in animal models of HIV latency. Efforts seek to develop cellular or gene therapies to control or clear infection, strategies to permanently silence viral genomes, induce apoptotic death in infected cells, or allow viral remission in the absence of viral eradication. However, this overview will more narrowly focus on efforts to develop curative therapy that targets and eliminates the persistent reservoirs of HIV infection. Pilot human trials seeking to reverse HIV latency and deplete the reservoir of persistent infection have begun, but there is still more to learn and much to be done.

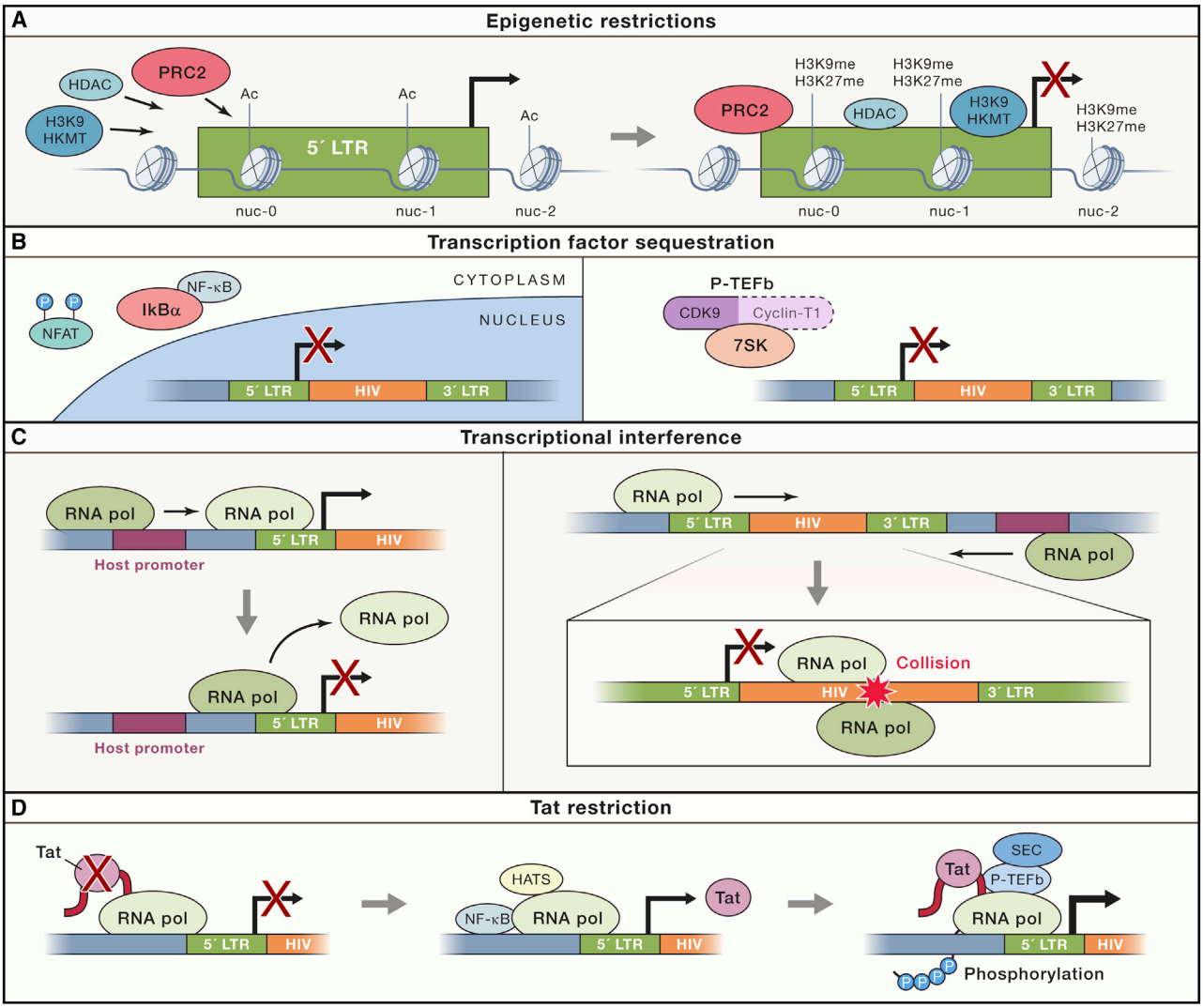

Figure 1. Proviral Silencing and Latency Are Founded and Enforced via Multiple Restrictions to Expression

(A) Epigenetic modifiers, such as histone deacetylases (HDACs) and histone lysine methyltransferases (HKMTs), are recruited to the HIV-1 LTR promoter, notably by the PRC2 complex. This results in histone modifications within chromatin at the HIV promoter that limit the ability of RNA polymerase to initiate transcription.

(B) Sequestration of essential transcription factors like NFAT and NF-κB and the pTEF-b cyclin complex are sequestered in resting $CD4^+$ T cells by cellular regulatory complexes (IkB and HEXIM/7skRNA, respectively).

(C) Transcriptional interference can occur by promoter occlusion, when a host gene polymerase positioned upstream of the provirus reads through the HIV-1 LTR, causing displacement of necessary transcription factors. Alternatively, convergent transcription abort viral expression when the proviral and the host gene RNA polymerase II (Pol II) complexes are in opposite orientation and collide.

(D) In the absence of sufficient viral Tat, viral transcripts are paused. The switch to processive elongation requires the kinase activity of P-TEFb along with recruitment of processivity factors that constitute the super elongation complex (SEC). Tat efficiently *trans*-activates HIV transcription by recruiting P-TEFb and the SEC to the paused RNA Pol II complex at the TAR hairpin.

The Current State of HIV Cure Research

Among the countless infection events that occur within an untreated HIV-infected individual, a select few result in integration of a fully intact, functional provirus that establishes stable infection with negligible viral gene expression. Most viral genomes that can be measured are defective because of errors in viral reverse transcription that result in small deletions or mutations or through large deletions caused by the effects of the host APOBEC3 proteins. The rare surviving intact viral genomes persist within cellular reservoirs. By definition, these latent proviruses can revert to the productive state *in vivo* but, during latency, are unaffected by ART and unable to be detected by the host immune response. This state of proviral latency has been quantitated in peripheral blood and lymphoid tissues of HIV-infected subjects, and an array of molecular mechanisms that allow establishment and maintenance of persistent, latent HIV infection have been described (Figure 1; Ruelas and Greene, 2013; Mbonye and Karn, 2014). Evidence that cellular factors are

Table 1. Research toward a Cure Trials of January 30, 2020

Combination LRA and Immunotherapy Trials	Trial Registry Identifier(s)	Sponsor(s)	Phase	Estimated End Date
Maraviroc, dolutegravir, dendritic cell vaccine, auranofin, nicotinamide	NCT02961829 (closed)	Federal University of São Paulo	not listed	March 2020
ROADMAP: romidepsin + 3BNC117	NCT02850016 (closed to enrollment)	Rockefeller University	phase IIa	December 2019
TITAN: lefitolimod + 3BNC117 + 10-1074 (TLR9 agonist + bnAbs)	NCT03837756	University of Aarhus	phase IIa	February 2021
eCLEAR: romidepsin + 3BNC117	NCT03041012	Aarhus University Hospital	phase II	April 2021
Research In Viral Eradication of HIV Reservoirs (RIVER): ART, ChAdV63.HIVconsv and MVA.HIVconsv vaccines, vorinostat	NCT02336074 UK CPMS18010 (closed)	Imperial College London	phase II	November 2022
iHIVARNA, MVA vector HIV vaccine, 10-1074, romidepsin, HIVACAR01 (personalized HIV RNA vaccine)	NCT03619278 (not yet open)	David Garcia Cinca	phase I/IIa	July 2020
N-803 (recombinant human superagonist interleukin-15 complex), VRC07-523LS, PGT121, haploidentical NK (haNK) cells	NCT04144335 (not yet open for enrollment)	University of Minnesota	phase Ib	December 2020
Chidamide + CAR T or TCR T cell therapy	NCT03980691	Guangzhou 8th People's Hospital	phase I	December 2021
VRC07-523LS + vorinostat	NCT03803605	University of North Carolina, Chapel Hill	phase I	July 2022
Vorinostat + HXTC: HIV-1 antigen expanded specific T cell therapy	NCT03212989	University of North Carolina, Chapel Hill	phase I	June 2021
Vorinostat ± tamoxifen in postmenopausal women	NCT03382834 (closed)	NIAID	phase I	June 2023
Vacc-4x + romidepsin	NCT02092116	Bionor Immuno AS/Celgene	phase I/II	2019
AGS-004 + vorinostat	NCT02707900	University of North Carolina, Chapel Hill	phase I	2019
MVA.HIVconsv + romidepsin	NCT02616874	IrsiCaixa	phase I	2017

Source: Treatment action group (https://www.treatmentactiongroup.org/cure/trials/).

required to maintain quiescence implies that proviral latency is an unstable state of HIV infection amenable to therapeutic attack.

The most studied strategy to eliminate the persistent reservoir of infection seeks to pair therapies that induce expression of latent HIV with continued ART to prevent infection of new cells while augmenting clearance of infected cells, now identifiable because of their production of viral antigen. HIV latency reversal agents (LRAs) have been developed to accomplish the first step of this process: induce expression of the virus within reservoirs. Because viral latency is driven by host cellular programming, LRAs must be targeted to host processes, analogous to many agents designed for use in oncology. Although the LRAs tested to date are capable of inducing expression of RNA or viral protein from latent viral genomes *in vitro* and *in vivo*, none have yet convincingly depleted the viral reservoir or extended virologic remission after treatment interruption (Rasmussen and Søgaard, 2018). LRAs must be carefully selected to avoid unacceptable off-target toxicities. Therefore, identification of new approaches that potently and selectively induce HIV expression would represent a significant advance in progress toward an HIV cure. Ideally, LRAs might also potentiate clearance mechanisms to facilitate reduction of the reservoir, but, at a minimum, they should not impede viral clearance (Clutton and Jones, 2018).

Emblematic of the early state of the field, few studies have paired LRAs with a viral clearance strategy (Table 1). In one pilot study (Fidler et al., 2020) and reports of two others employing broadly similar approaches (B. Mothe et al., 2017, Conference on Retroviruses and Opportunistic Infections, abstract; Gay et al., 2020), depletion of latent, persistent infection was not seen. Although latency reversal activity appears to be measurable as an increase in HIV RNA expression within circulating lymphocytes, it is unclear whether this response will translate to sufficiently robust and durable HIV-1 protein expression to enable immune clearance of infected cells. Further, immune responses induced by the immunotherapies tested to date may have been insufficient to identify and clear such challenging targets. New tools and approaches are needed, and recent insights into the biology of HIV latency may offer a path toward more effective viral clearance strategies.

Multiple Mechanisms May Lead to Proviral Latency and Persistent HIV Infection

Initially, HIV infection was only understood to have a clinically latent phase prior to the appearance of AIDS. The development of RNA PCR enabled the recognition that viremia persisted throughout HIV infection, but the state of post-integration viral latency was not clearly recognized until 1995 (Chun et al., 1995).

Persistent and latent infection was thought to be established when productively infected, activated CD4+ T cells returned to the resting G_0 state, where minimal transcription of viral genes was expected. Consistent with this notion, in resting CD4+ T cells, various host transcription factors critical to driving HIV transcription, including nuclear factor κB (NF-κB), NFAT, and P-TEFb, are sequestered, present at low levels, and/or lacking posttranslational modifications necessary for full activation. However, proviral latency has been shown to be driven by more than simply a deficiency of transcription factors in the environment of a resting cell.

Epigenetic Controls

Shortly after the histone code hypothesis was put forward (Jenuwein and Allis, 2001), repressive epigenetic modifications at the chromatin of the HIV promoter (long terminal repeat [LTR]) was appreciated to play a key role in establishing and enforcing HIV latency. At the level of chromatin, histone acetylation is largely absent because of recruitment of histone deacetylases (HDACs) to the LTR (Turner and Margolis, 2017).

The proviral promoter is bound by three nucleosomes (Nuc-0, Nuc-1, and Nuc-2) that flank two DNase hypersensitivity regions. Extensive work in cell model systems has shown that HIV latency can be enforced by marking of the nucleosomes at the LTR with either of the major repressive posttranslational modifications: methylation at histone 3 lysine 27 (H3K27me) or at histone 3 lysine 9 (H3K9me) or by the recently identified mono-methyl mark of histone 4 lysine 20 (reviewed in Turner and Margolis, 2017). Whether these histone methyl marks can co-exist on the same nucleosomes *in vivo* or to what extent chromatin restriction is dependent on or affected by the viral integration site is currently unknown. However, interestingly, recent work suggests that both H3K27me and H3K9me and the epigenetic factors that write and read these marks are critical for the establishment and maintenance of HIV latency in primary cells (Nguyen et al., 2017). The removal of repressive histone methylation is far less understood; however, a role of the H3K9 demethylase LSD1 and the H3K27 demethylase UTX has been suggested (Boehm and Ott, 2017).

Although the switch between activating histone acetylation and repressive deacetylation has been understood as a key epigenetic driver in HIV latency, less is known about other histone marks. A histone modification more recently described, histone crotonylation, is a chromatin mark recently linked to de-repression of HIV transcription (Jiang et al., 2018). Although work on histone crotonylation is an emerging area of research, this could suggest that the use of crotonyl-coenzyme A (CoA) represents an alternative pathway to proviral activation when acetyl-CoA is limiting and efficient histone acetylation can otherwise not be achieved.

Other chromatin remodelers have been linked to HIV latency. BAF (BRG1- or BRM-associated, ATP-dependent factor) can be selectively recruited to the HIV LTR by the short isoform of bromo- and extra-terminal domain protein 4 (Conrad et al., 2017). The presence of the BAF complex can position the critical HIV nucleosome Nuc-1 at a less energetically favorable DNA sequence, aiding enforcement of transcriptional repression. Deepening our understanding of the epigenetic regulation of HIV expression may yield additional targets for HIV latency reversal therapies.

Other Limiting Factors for Viral Transcription

Although proviruses can be reactivated by epigenetic changes without cellular activation, a limitation of this approach is that epigenetic agents induce expression in a minority of proviruses compared with cellular activation signals. T cell activation mediates a cascade of T cell receptor (TCR) signaling events that are generally expected to relieve all restrictions to proviral expression. Induction and binding of NF-κB and SP1 as well as other host transcription factors to the LTR results in sufficient transcriptional initiation and elongation to produce the HIV activator protein Tat. Tat subsequently recognizes and binds a viral RNA structure, TAR (Tat-associated region), found at the 5′ end of the viral transcript. The Tat/TAR interaction initiates a positive feedback loop at the LTR via Tat-mediated recruitment of host cell factor P-TEFb, the super elongation complex, and SWI/SNF-activating complex PBAF. These factors collaborate to drive sustained productive elongation from the viral promoter. Remodeling of the repressive chromatin environment at the LTR occurs during this process via recruitment of the histone acetyltransferases CBP/p300 by NF-κB independent of Tat production, followed by Tat-mediated recruitment of additional acetyltransferases (Mbonye and Karn, 2014).

Perversely, the expectation that robust T cell activation would promptly activate expression of all latent proviral genomes was shattered by the demonstration of non-induced proviruses in 2013 (Ho et al., 2013). In a single round of stimulation *in vitro*, Ho et al. (2013) demonstrated that a minority sub-population of fully replication-competent proviral genomes still failed to be expressed, despite supraphysiologic cellular activation. Ho et al. (2013) carefully showed that these non-induced proviruses lacked sequence defects or other identifiable factors (e.g., DNA methylation) to explain their lack of response to cellular activation. However, additional rounds of stimulation *in vitro* did yield expression of additional proviruses, with diminishing returns over subsequent rounds of induction. This finding highlighted the possible challenges of re-activating 100% of latent proviruses *in vivo*. The ''failure to activate'' of a portion of the proviral population was hypothesized to be due to an underlying stochastic behavior of this viral biologic system (Razooky et al., 2015). However, an alternate explanation is simply that there are numerous factors contributing to inhibition or required for expression and that multiple rounds of signaling are required to hurdle all these barriers in 100% of a viral population. The practical question, as yet unanswered, is how long this will take. Bradley et al. (2018) identified diverse transcriptomic environments that were significantly associated with proviral latency but prominently included a transcriptional signature of naive and central memory T cells. In this model system, viral genomes that were stimulated to leave latency often returned to quiescence when the stimulus was withdrawn. A deeper understanding of these cellular programs may lead to new and more effective approaches to reverse latency. Finally, it must be said that nearly all of the observations of mechanisms of HIV latency have been made in *in vitro* model systems. It remains to be seen which of these mechanisms is the most relevant *in vivo* and which can be safely modulated for therapeutic purposes.

The Latent Reservoir Is Unexpectedly Dynamic

Although LRAs ultimately act at the level of proviral transcription, they do so in the context of the host cell environment. Therefore, it is also important to understand the cells that play host to persistent HIV. Although most HIV target cells exist within tissue, nearly all studies of HIV reservoirs are based on analyses of cells harvested from the peripheral circulation during suppressive ART. These studies reproducibly documented that all HIV-infected people on ART have an inducible viral reservoir that decays very slowly (Crooks et al., 2015; Siliciano et al., 2003), resides principally in resting central memory CD4+ T cells, and is largely comprised of defective DNA (Bruner et al., 2016; Ho et al., 2013). Further, reservoir formation cannot be prevented by even extremely early ART (Henrich et al., 2017; Luzuriaga et al., 2015). Although these studies yielded insights into the nature of persistent HIV-1 reservoirs during suppressive ART, until recently, little was definitively known about the dynamics of reservoir formation before and after ART, reservoir persistence, and the composition of the pool of cells encoding replication-competent but quiescent HIV over time.

The most common assumption was the simplest one: starting soon after transmission, the virus enters the latent reservoir—predominantly central memory CD4+ T cells—and remains latent until the cell dies or until some external stimulus induces viral expression from latency. If viral expression occurs, then there is some likelihood that the cell will be cleared because of viral cytopathic or immune clearance effects. These events eliminating infected cells from the reservoir are countered by events increasing the size of the reservoir; namely, activated infected cells returning to a resting state and re-entering the reservoir. These events must be in a slightly negative balance, as indicated by a slow decline in the reservoir over time on ART, uniformly seen in the presence of ART (Crooks et al., 2015; Siliciano et al., 2003).

However, a second major force shaping the population of the persistent, latent proviral reservoir is now known to be clonal proliferation, also termed clonal expansion. Proliferation of cells harboring HIV may be driven by the natural homeostatic proliferation of T cells, by adaptive antigen-induced T cell proliferation, or, less likely, by dysfunctional CD4+ cell proliferation triggered by an HIV integration event in a critical genomic site. Whatever the cause(s), cell duplication has been demonstrated to be a mechanism of sustaining the long-lived, stable reservoir (Maldarelli et al., 2014; Wagner et al., 2014). Consistent with this, residual viremia is often dominated by clonal sequences, and sequencing of proviral DNA also reveals clonal expansion of identical viral sequences (Tobin et al., 2005; Bailey et al., 2006). Although it appears that clonal expansion favors defective proviruses (Bruner et al., 2019), expansion of replication-competent clones (Simonetti et al., 2016; Hosmane et al., 2017; Bui et al., 2017) appears to be sufficient to maintain the longevity of the viral reservoir.

One aspect of this model was recently challenged by several studies showing that HIV does not enter the durable latent reservoir at a constant rate over time prior to initiation of ART (Abrahams et al., 2019; Brodin et al., 2016). Both studies longitudinally examined HIV-1 RNA in the plasma of people prior to ART (n = 10, Brodin et al., 2016; n = 9, Abrahams et al., 2019) and compared this pre-ART virion RNA with either viral DNA persisting after at least 2 years of ART (Brodin et al., 2016) or replication-competent virus recovered from rCD4+ T cells isolated from the blood after approximately 5 years of ART (Abrahams et al., 2019). In both studies, the majority of the persistent reservoir, observed as either proviruses or inducible viruses, was most closely related to variants isolated from the plasma near the time of ART initiation. Further, based on detailed phylogenetic analyses, Abrahams et al. (2019) were able to show that approximately 80% of the replication-competent reservoir appeared to originate from viruses circulating in the plasma in the year prior to ART, although a minority of vial genomes were found in the reservoir that were closely related to viruses circulating much earlier in untreated infection. Most recently, a third cohort demonstrated very similar findings (Pankau et al., 2020).

These results may be explained by a new view of latency where ART initiation fundamentally changes the rate at which HIV-infected cells enter latency and the rate at which proviruses become reactivated and expressed, leaving the reservoir. Prior to ART, infected cells enter and exit at a relatively constant rate, with entry being governed by high rates of infection prior to ART. Exit from the reservoir in the pre-ART state is hypothesized to be driven by immune activation that favors viral expression and/or cell death. Under these conditions, prior to ART, the frequency of latent infection (“size of the reservoir”) reaches homeostasis, but the specific viral genomes in the reservoir are continually replaced by viruses entering from the recently circulating pool (Figure 2).

In this model, ART initiation alters this equation by blocking new infections, terminating entry of new viral genomes into the reservoir. However, a new setpoint is reached as exit from the reservoir is slowed by an indirect effect of ART by at least one of several mechanisms: (1) enhanced entry of integrated proviruses into latency because of changes in the cell signaling milieu and cellular gene expression programs, (2) gradual enforcement of latency by epigenetic marks laid down over time, and (3) the extension of CD4+ T cell half-life (including HIV-infected CD4+ T cells; Figure 2) that accompanies viral suppression. The broad effects ART-mediated suppression of viremia on the immune system are likely to play a role in the establishment and behavior of the latent, persistent cellular reservoir. Ablation of viremia may extend the half-life of HIV-infected cells by restoring the ability to form long-lived memory cells (Abrahams et al., 2019; Goonetilleke et al., 2019). Alternatively, or additionally, the general dampening of immune activation and the reduction of circulating viral antigen that is mediated by ART may create an intracellular environment that allows epigenetic silencing of the proviral integrant and is less favorable for proviral expression. Together, the reduction of entry and exit may stabilize the reservoir and allow it to form the long-lived reservoir that will persist during prolonged ART. Further, slowing exit from the reservoir skews long-lived reservoir composition toward viruses that have most recently entered latency from the circulating pool. Nevertheless, it would be expected that a small number of older, earlier proviruses could be found to persist, as reported by Abrahams et al. (2019).

The mechanisms by which ART indirectly recalibrates exit from the reservoir are currently unknown but, when identified,

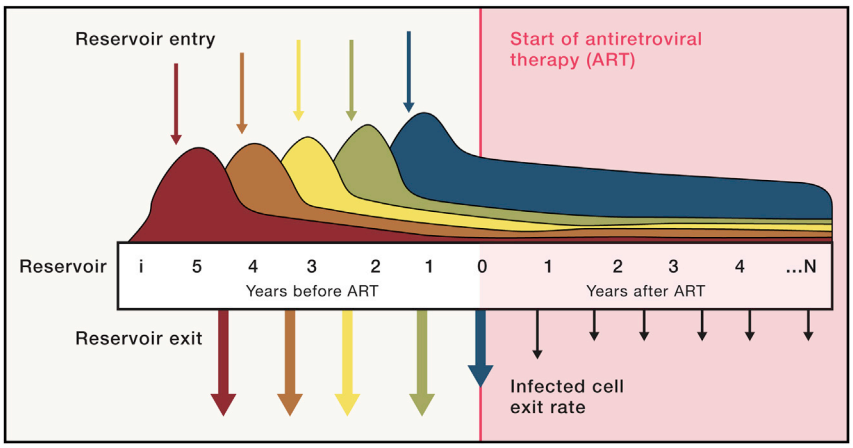

Figure 2. A Model of the Dynamic, Latent Reservoir

Viruses enter the latent, persistent reservoir from the earliest days of infection, but most do not persist because of a short half-life of the host cells, immune activation, or both. Early viruses are serially replaced by viruses that circulate later in infection, prior to ART initiation (dotted line). Upon ART initiation, viruses no longer enter the reservoir as replication is blocked. The exit rate of infected cells is much decreased, perhaps because of dampening of generalized immune activation and/or increases in $CD4^+$ cell half-life. The slower loss of persistently infected cells is thereafter nearly matched by homeostatic proliferation, resulting in slow decay of latent viruses.

may inform strategies for reducing the size of the reservoir. Although the specific mechanisms by which ART indirectly extends the half-life of latently infected cells must be confirmed, it may be possible to use this new observation to design interventions deployed near the time of ART and tip the balance away from latency enforcement, allowing the latent reservoir to shrink. For example, blockade of interleukin-7 (IL-7)/IL-7R signaling could prevent the transition of CD4+ T cell effectors to the memory cell pool and their subsequent homeostatic maintenance. Such a blockade, for a relatively limited period of time (e.g., several months), might block enforcement of latency and, thereby, formation of the majority of the long-lived reservoir (Abrahams et al., 2019; Goonetilleke et al., 2019). Development of strategies to counter these effects may require interventions deployed near the time of ART to tip the balance away from latency enforcement, allowing the latent reservoir to shrink or prevent HIV-infected cells from becoming long lived.

The Diverse Cells of the Latent Reservoir

The first definitive studies that proved the existence of an inducible, replication-competent HIV reservoir were performed in memory CD4+ T cells lacking activation markers (Chun et al., 1997a; Finzi et al., 1997; Wong et al., 1997) To date, this cell population remains the most well-characterized reservoir of latent HIV. These long-lived cells have an estimated half-life of 3.7 years and represent a stable source of virus capable of reigniting infection in the absence of suppressive therapy. Within the CD4+ T cell compartment, central memory T (TCM) cells have been most carefully studied longitudinally as a latent reservoir (Crooks et al., 2015; Siliciano et al., 2003). Other populations of T cells, such as naive T (TN) cells, T memory stem (TSCM) cells, transitional memory T (TTM) cells, effector memory T (TEM) cells, gamma/delta T cells, and T regulatory (Treg) cells are all potential sources of persistent HIV infection (Buzon et al., 2014; Chomont et al., 2009; Soriano-Sarabia et al., 2014; Tran et al., 2008; Zerbato et al., 2019), although the frequency of replication-competent provirus has been less fully quantitated. Although the stability of the reservoir in resting TCM cells has been carefully studied, the same cannot be said for individual T cell populations, a matter complicated by the natural differentiation process of T cells into various compartments (e.g., central memory to effector memory) and the likelihood that a latent proviral genome may sometimes remain quiescent as an infected cell transitions in to the effector pool or returns to the memory pool.

Studies aimed at measuring the stability of the latent reservoir in different T cell populations face the added hurdle of reconciling observations made in cells captured at a snapshot in time with the natural fate of that cell. Although TEM cells generally have a shorter half-life compared with TCM cells (Farber et al., 2014), a higher frequency of integrated HIV DNA and inducible provirus in this compartment in people on ART has been reported (Hiener et al., 2017). TEM cells were also found to produce the highest quantities of HIV p24 capsid antigen following phorbol myristate acetate/ionomycin stimulation (Pardons et al., 2019). Interestingly, differentiating TCM cells into a TEM cell phenotypes *in vitro* promotes more efficient reactivation of HIV by LRAs (Kulpa et al., 2019). TEM cells also have higher levels of histone acetylation in their basal state (Pardons et al., 2019). However, direct evidence that proviral genomes found in TEM cells are either expressed *in vivo* more often or to higher levels or without robust stimulation has not been fully elucidated. One model that fits these observations but is still unproven is that individual infected TEM cells are not long lived, but are continuously replaced by persistent and proliferating TCM cells that are differentiating into TEM cells (Figure 3).

Most of what is known about the different populations of cells contributing to the HIV reservoir has been determined using peripheral blood. Recently, however, studies have been undertaken to better characterize the tissue reservoir (Figure 4). Memory CD4+ T cells expressing the chemokine receptor CCR6 have been reported to be a source of persistent HIV in gut tissues (Anderson et al., 2020; Gosselin et al., 2017), as are non-CD4+ T cells (Yukl et al., 2013). Located within the B cell follicle of secondary lymphoid organs, T follicular helper (Tfh) cells have been reported to be an HIV reservoir even in the context of anti-retroviral therapy (Banga et al., 2016; Pallikkuth et al., 2015). Given the limited access of immune effector cells into the B cell zone, clearing persistently infected Tfh cells may be a special challenge. Finally, in a recent study consistent

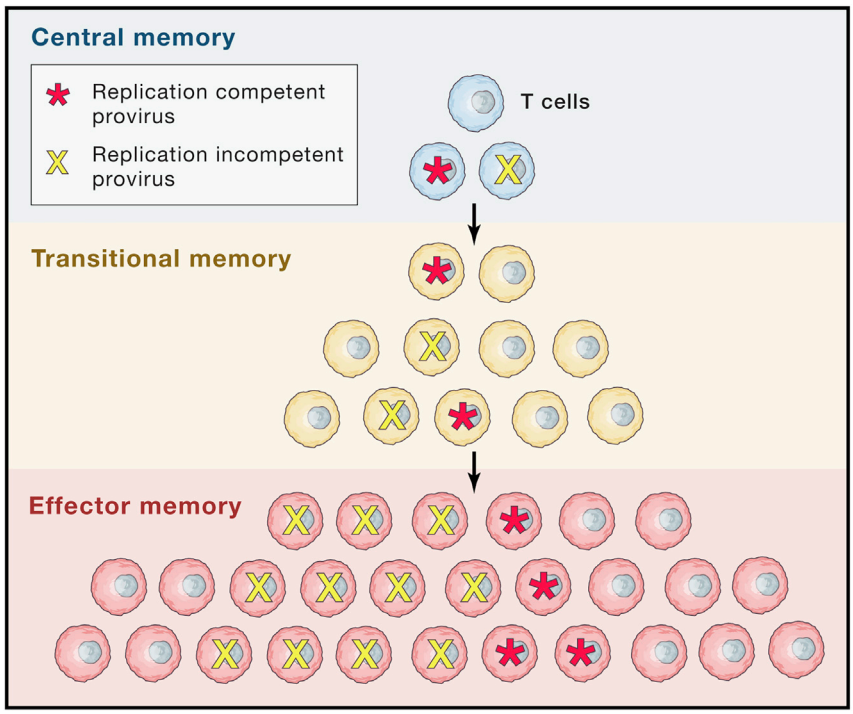

Figure 3. Persistence and Proliferation in Latency

Homeostatic and antigen-driven proliferation appear to contribute to the persistence of proviral infection. One model that fits current observations holds that, although more differentiated, activated effector cells may have a shorter lifespan, they may be continually replaced by clonal proliferation of less differentiated memory cell populations.

with studies of animal models (Abreu et al., 2019; Honeycutt et al., 2017), Ganor et al. (2019) used penile tissue from ART--treated individuals undergoing elective gender reassignment surgery to demonstrate the presence of replication-competent HIV in urethral macrophages. This suggested that cells of the myeloid lineage are a potential source of persistent HIV infection despite ART. As investigators seek to reverse latency and clear persistent infection in the well-defined latent reservoir within TCM cells, attention must be given to the effects of such interventions on provirus in other populations. It is possible that efforts that yield depletion of the latently infected TCM cell pool may lead to depletion of infection in other, more differentiated cell types or that these other reservoirs require alternate interventions.

Targeting Privileged Sites

There has long been concern regarding the ability to eliminate HIV from unique body compartments, especially the CNS and the genital tract (Wong and Yukl, 2016). The biology of the CNS has fueled suspicion that HIV may persist in this compartment during long-term ART and generate viral rebound after treatment interruption, but, until recently, there was little evidence to support this hypothesis. It has long been known that HIV-infected macrophages can be found in the CNS prior to ART (Joseph and Swanstrom, 2018), and given the putatively long half-life of macrophages and the fact that there is a low density of T cells in the CNS to eliminate HIV-infected cells, it has been hypothesized that HIV-infected macrophages persist in the CNS long after ART is initiated.

Consistent with this hypothesis, multiple studies have identified viral DNA and RNA in the CNS of HIV-infected humans and simian immunodeficiency virus (SIV)-infected macaques after extended ART (Estes et al., 2017; Lamers et al., 2016). Further, HIV continues to replicate in the CNS of a small percentage of otherwise well-suppressed people on ART (Joseph et al., 2019). Recently, the persistence of replication competent virus in the CNS was confirmed by viral outgrowth assays, illustrating that SIV can be cultured from macrophages isolated from the CNS of ART-treated pigtailed macaques infected with a highly pathogenic SIV (Avalos et al., 2017), but analogous studies have not been performed using human brain tissue. Together, these findings indicate that replication-competent viral reservoirs may persistent in the CNS during ART, but it remains unknown how large this reservoir is and the diversity of cells types (e.g., macrophages, microglia, astrocytes, or CD4+ T cells) that populate it.

Several lines of evidence demonstrate that the genital tract may also serve as a unique compartment. In parallel to what is known about CNS reservoirs, urethral macrophages isolated from penile tissue after at least 3 years of ART have been shown recently to harbor replication-competent, inducible HIV-1 proviruses and RNA (Ganor et al., 2019). In addition, HIV RNA can be readily recovered from genital fluids in men and women in spite of successful suppression of HIV in the blood. Detection of viral RNA in the genital tract may be due to viral replication in the presence of non-inhibitory drug concentrations in this compartment, a possibility supported by observed variation in the ability of drugs to accumulate in this compartment and the fact that protease residence mutations can be detected in the semen of some men on protease inhibitor-based regimens with undetectable plasma viral loads (Houzet et al., 2014). Alternatively, and more likely, cells harboring HIV may simply release HIV into the genital tract. Regardless of whether there is viral replication in the genital tract during ART, there is growing evidence that HIV-infected cells can persist in that compartment during ART.

The Evolving Approach to Inducing Latency Reversal

To rigorously demonstrate the existence of latent HIV infection, initial studies in the 1990s were carried out in carefully purified resting CD4+ T cells. In this cell population, reversible silencing of viral expression in the cells under study—the true definition of latency—could be clearly demonstrated. Because the integrated, latent HIV provirus in T cells is responsive to activation

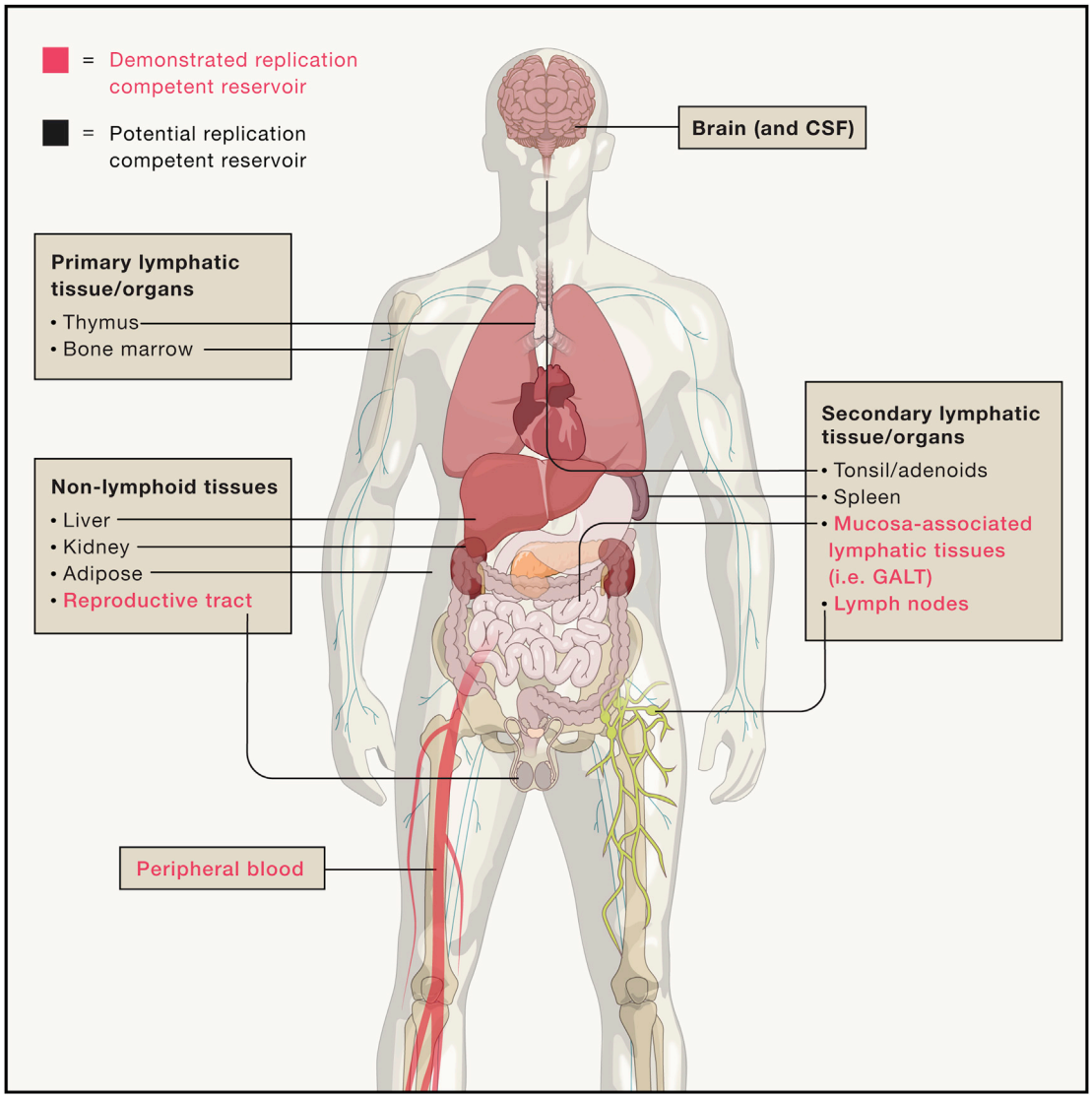

Figure 4. Potential and Demonstrated Sites of HIV Reservoirs

Anatomic sites with demonstrated recovery of replication-competent virus in humans following years of suppressive ART are highlighted in bold. Potential replication-competent anatomic reservoir sites are shown in regular font. These sites represent tissues/organs where HIV nucleic acid has been detected in humans or animal models, but recovery of rebound-competent virus in humans after years of suppressive ART has not been demonstrated.

of immune signaling pathways, latency in resting central memory CD4+ T cells was reversed using the TCR agonist phytohemagglutinin (PHA) or anti-CD3 antibodies (Chun et al., 1997b; Finzi et al., 1997; Wong et al., 1997). These observations led to the first proposals for strategic HIV eradication therapy (Hamer, 2004), and the first clinical trial seeking to clear HIV infection studied the effects of the anti-CD3 antibody OKT3 and IL-2 (Prins et al., 1999). However, the strategy of global T cell activation proved to be untenable because this first clinical trial resulted in profound T cell activation and depletion and a substantial increase in inflammatory cytokine production accompanied by severe toxicities (van Praag et al., 2001). Attempts to purge the viral reservoir then fell by the wayside for a time, but the emergence of the role of epigenetic control of proviral persistence led to renewed effort to reverse viral latency without global T cell activation.

Epigenetic LRAs

Seeking to avoid global cellular activation, the next LRAs to emerge targeted the chromatin restrictions that maintain HIV latency. The epigenetic LRAs fall into three groups: (1) HDAC inhibitors (HDACis), (2) histone methyltransferase inhibitors (HMTis), and (3) bromo- and extra-terminal domain inhibitors (BETis). Of the three groups, only HDACis are currently in clinical trials for specific evaluation as LRAs. Current HDACis are pan-inhibitors and include, among others, vorinostat, panobinostat, belinostat, and romidepsin, some of which are approved for treatment of T cell lymphomas (Rasmussen and Søgaard, 2018). HDACis have been shown to induce HIV activation

in vitro and induce detectable cell-associated HIV RNA *in vivo*; however, HDACis as single agents have failed to measurably decrease the size of the viral reservoir. This is likely due to the failure to engage an effective viral clearance response, but the possibility remains that these agents are ineffective *in vivo*. It is important to note that these clinical trials have reported minimal safety concerns regarding HDACis *in vivo*.

Currently, there are no US Food and Drug Administration (FDA) approved HMTi or BETi trials directed at HIV infection; however, pre-clinical small-molecule HMTis, including GSK-343 and EPZ-6482 targeted to EZH2, the HMT responsible for H3K27me, and UNC-0638, an inhibitor targeted to H3K9 HMT G9a, have been demonstrated to reactivate HIV in laboratory models of latent infection (Nguyen et al., 2017; Turner and Margolis, 2017). Similarly, BET inhibitors have also been demonstrated similar latency reactivation activity *in vitro* (reviewed in Boehm et al., 2013), but interest in evaluating HMTis and BETis as LRAs will likely depend on tolerability observed in ongoing oncology trials. Should these epigenetic LRAs advance to the clinic, there may be an opportunity for testing in combination with HDACi, other classes of LRAs, and/or immune-modulating therapies to identify synergistic relationships that may allow lower and/or less frequent dosing strategies to limit adverse events.

Signal Agonist LRAs

Given the incomplete success of epigenetic inhibitors in mediating robust and universal latency reversal, efforts have continued to develop safer strategies to reverse latency through the use of cellular signaling pathways. Activation of protein kinase C (PKC) engages many of the signaling pathways induced by natural activation of the TCR. Small-molecule PKC agonists (PKCas), such as phorbol esters and diterpenes, have been studied for HIV latency reversal and have been shown to readily induce T cell activation and HIV expression in the laboratory setting across a range of model systems (Jiang and Dandekar, 2015). However, progression of PKCas to preclinical and clinical studies has been limited because of the potential for dangerous side effects of broad and potent PKC activation.

Bryostatin-1 is a potent molecule studied in a large number of clinical trials for several indications, including oncology and Alzheimer's disease, and has been studied for HIV latency reversal. In a humanized mouse model, bryostatin-1 and an analog induced HIV expression but at doses that are only slightly lower than lethal exposures (Marsden et al., 2017). A cautious clinical trial of bryostatin-1 studied very low doses that did not lead to activation of the immune system but also did not induce HIV expression (Gutiérrez et al., 2016). Ingenol B and the stabilized derivative GSK'445A have been reported to induce SIV expression in ART-suppressed, SIV-infected macaques, accompanied by strong cellular activation, cytokine production, and unacceptable clinical signs such as fever (L.P.S. Gama et al., 2015, Conference on Retroviruses and Opportunistic Infections, abstract; J.T.V. Brehm et al., 2017, Conference on Retroviruses and Opportunistic Infections, abstract; A. Okoye et al., 2018, AIDS 2018, abstract). Recently, Jiang et al. (2019) found evidence of latency reversal in the skin of patients treated with topical ingenol mebutate as part of an actinic keratosis regimen, demonstrating that, in a setting where PKCas can be administered safely, HIV expression can be induced. Others are currently pursuing ingenols administered as part of a traditional Chinese herbal preparation, kansui tea, in primate studies and clinical trials (NCT02531295). Although PKCas are genuine LRAs with *in vivo* activity, the relatively small window between efficacious and toxic exposure makes clinical development unacceptable in an otherwise healthy population of ART-treated people living with HIV (PLWH) infection.

In another approach to signal CD4+ cells and disrupt HIV latency, similar to the earlier use of IL-2, administration of IL-7 has been explored. It has been found to have some LRA activity *in vitro* (Lehrman et al., 2004; Wang et al., 2005), but this effect was overshadowed *in vivo* by the parallel CD4+ cell proliferation induced by the cytokine, thwarting its use in viral eradication strategies (Katlama et al., 2016). More recently, research in oncology has brought into clinical testing several engineered forms of IL-15, including a heterodimeric form of the molecule (Thaysen-Andersen et al., 2016) and a synthetic receptor superagonist (ALT-803) (Rhode et al., 2016). There is significant evidence that use of forms of IL-15 may confer immunological benefits, perhaps augmenting the antiviral immune response and improving clearance of persistent infection (Garrido et al., 2018; Watson et al., 2018). However, there is less evidence that IL-15 can, by itself, directly reverse HIV latency *in vivo* (Webb et al., 2018). Nevertheless, because of its immunomodulatory properties, further study of this cytokine as part of a latency reversal and viral clearance strategy appears warranted, and selected studies in people with HIV are underway.

Toll-like receptor (TLR) agonists have been studied as an orthogonal approach with the potential for HIV latency reversal activity and as immunomodulators capable of augmenting an antiviral response. TLRs are pathogen recognition receptors that sense molecular motifs conserved across microbial organisms and mediate signaling responses (Macedo et al., 2019). Both *in vitro* and *in vivo*, TLR agonists increase immune activation, induce innate antiviral responses, and can augment pre-existing adaptive ones. However, reminiscent of the experience with IL-15, while there is *in vitro* evidence that selected TLR agonists can reverse viral latency, there has only limited *in vivo* evidence for LRA activity so far (Vibholm et al., 2019). However, because of the unique immunomodulatory properties of TLR agonists, further study of this approach to combination latency reversal and viral clearance strategies is warranted, and selected studies in people with HIV are underway.

Most recently, efforts to directly trigger cell signaling pathways for activation of HIV expression without the pleiotropic effects of PKCas have been renewed. Among the transcription factors activated by TCR ligation or PKCas, NF-κB has been described to play a critical role in inducing HIV expression (Williams et al., 2004). Selective activation of NF-κB would thus induce HIV expression but spare activation of additional pathways, perhaps minimizing the side effects of a latency reversal regimen *in vivo*. Pache et al. (2015) reported a class of small molecules known as SMAC mimetics or IAP agonists that selectively activate the non-canonical NF-κB signaling pathway and induce HIV expression in cell line model systems. Sampey et al. (2018) studied a range of IAPis originally discovered to promote tumor cell apoptosis and found that AZD5582 potently induces HIV

expression in cell line models and in CD4+ T cells isolated from ART-suppressed HIV-infected study participants. An optimized dosing strategy for application in humanized mice and rhesus macaques was developed and demonstrated that AZD5582 activates the non-canonical NF-κB pathway *in vivo* at tolerated doses. In ART-suppressed HIV-infected humanized mice and SIV-infected rhesus macaques, AZD5582 robustly induced HIV or SIV expression, as evidenced by periods of detectable plasma viremia and increased viral RNA in resting CD4+ T cells isolated from tissues (Nixon et al., 2020). Importantly, induction of both HIV or SIV in each model system occurred in the absence of substantial inflammatory cytokine induction and in the absence of robust cellular activation and was generally well tolerated. These findings demonstrate that IAPis can repeatedly induce HIV expression in regimens that are tolerated in the two leading animal models of HIV persistence. Further animal model studies are underway in combination with clearance agents as well as progression toward clinical studies.

Augmenting Immune Responses to Clear Persistent Infection

The clearance of residual HIV infection that remains despite effective and prolonged suppression of viral replication by ART is a unique challenge for the immune system and for immunotherapeutic agents. In the current paradigms of therapies to disrupt latency and clear persistent infection, the targets for clearance are rare populations of cells induced by LRAs to express HIV proteins in quantities that are likely to be limited. Immunologic "danger signals" to recruit effectors to the site of the pathogen may be absent or limiting. Further, these cell populations may be widely distributed across anatomical compartments, and the HIV-specific immune response may have waned in the absence of recent antigen exposure and/or may be dysfunctional or depleted.

CD8+ T Cells

CD8+ T cells play a major role in control of HIV viremia, and early T cell responses exert significant immune pressure on HIV-1, reflected by emergence of viral escape variants within weeks (Goonetilleke et al., 2009). The rate of virus escape has been used to infer the level of CD4+ T cell killing in mathematical models, suggesting that primary HIV-1-specific CD8+ T cells can kill up to 30% of virus-infected cells per day (Goonetilleke et al., 2009). However, in the vast majority of individuals, CD8+ T cell immunity is insufficient to durably control viremia. In turn, ongoing viremia contributes to the emergence of generalized CD8+ T cell dysfunction, including of loss of proliferative and cytolytic capacity.

Although ART largely restores CD8+ T cell function, CD8+ T cells of PLWH exhibit an immune-aging phenotype (reviewed in Warren et al., 2019). The frequency of HIV-1-specific CD8+ T cells remains stable over time in durably suppressed individuals, albeit at ~10-fold lower levels than untreated infection (Xu et al., 2019). Although little to no selective evolution of HIV is observed in durably suppressed individuals, T cell escape variants generated in untreated infection remain archived in the HIV-1 replication-competent reservoir (Deng et al., 2015; Meier et al., 1995), very likely compromising effective CD8+ T cell immunity following treatment interruption. An additional hurdle, detailed above, is that latently infected cells are rare and widely anatomically distributed. CD8+ T cells typically migrate in response to chemotactic signals produced by foci of replication. In an ART-treated individual (i.e., no virus replication), the inflammatory signal produced by rare HIV-infected cells may be insufficient to attract circulating T cells.

CD8+ T cell immunotherapies are being designed to address the challenges of viral eradication. Current therapies can be broadly divided into traditional therapeutic vaccine approaches that seek to boost and/or redirect HIV-1-specific CD8+ T cells or chimeric/biological approaches that harness non-HIV-1-specific CD8+ T cells to kill infected cells. Therapeutic vaccines seek to induce or boost T cells that target regions of HIV-1 that are highly conserved. The rationale here, which is based on extensive studies in natural infection, including studies of elite controllers, is that virus escape in conserved HIV-1 regions is slower because escape imparts a fitness cost to the virus. Therapeutic HIV vaccines include live-attenuated viral vectors, DNA vaccines, and dendritic cell and adoptive T cell therapy.

Multiple chimeric/biological approaches are being tested, including chimeric antigen receptors in which HIV TCRs are expressed in memory CD8+ T cells subverting their antigen and wherein CD3 T cells are re-directed to kill infected cells expressing HIV-1 proteins and/or presenting HIV-derived peptides. Harnessing the killing capacity of the nearest $CD3^+$ cell is a very attractive approach to overcome the challenge of the broad distribution of persistently infected cells. Cytokines such as IL-15, which have also been proposed for study as LRAs, may also promote access of CD8+ T cells to infected cells in B cell follicles in lymph node (Bronnimann et al., 2018).

Antibodies for Viral Clearance

Humoral responses are broadly divided into two classes of antibodies: those that (1) block infection by binding to the envelope of free viruses, called neutralizing antibodies (NAbs), and those that (2) recognize the envelope during virus entry or on the surface of infected cells (non-NAbs). The importance of these antibodies against HIV-1 has been demonstrated by passive protection studies in non-human primates (NHPs) and their ability to exert immune pressure and rapidly select virus escape variants. Protection studies have suggested that neutralization and Fc-mediated NAb effector functions cooperate in providing protection from SHIV infection (Moog et al., 2014). Non-NAbs could also limit the number of transmitted/founder isolates compared with the control (Santra et al., 2015). However, use of the broad NAbs 3BNC117 and VRC01 for treatment of HIV-1 infection revealed the presence of pre-existing escape mutants (Caskey et al., 2015; Lynch et al., 2015), and such pre-existing resistance might complicate the use of NAbs to eradicate persistent infection.

To overcome these limitations, engineered mAb-based molecules that could recognize multiple HIV-1 antigens or simultaneously redirect the cytotoxic cells to kill HIV-1-infected cells have been pursued (Ferrari et al., 2016). Bispecific T cell engagers (BiTEs) or dual affinity re-targeting (DART) molecules are novel small molecules designed to recognize infected cells and recruit effector cells (Ferrari et al., 2016). These molecules can eliminate cells that have been infected *in vitro* as well as

reactivated latently infected CD4+ cells obtained from ART-treated donors (Pegu et al., 2015; Sung et al., 2015b). DART molecules are currently being tested for safety (ClinicalTrials.gov NCT03570918) in a first-in-human clinical trial.

Innate Immune Responses

The first to be mobilized during acute HIV-1 infection, innate responses contribute to initial control of virus replication (Stacey et al., 2009). Among the first cytokines to reach peak plasma levels are the interferons and IL-15, which help activate natural killer (NK) cells (Garrido et al., 2018) and favor antibody engagement to mediate antibody-dependent cellular cytotoxicity (ADCC) (Fisher et al., 2019). NK cell immunity can be targeted for HIV clearance strategies in several ways. The cytotoxic effects of NK cells can be harnessed using chimeric antigen receptor (CAR) technology similar to that being used for T cells (Zhen et al., 2015). Administration of HIV-specific antibodies targeting membrane-associated proteins will likely harness NK cells to mediate ADCC to kill HIV-1-infected cells (Pollara et al., 2013). Again, IL-15, which activates NK cells to augment killing of HIV-1-infected cells (Garrido et al., 2018), could be administered with the above strategies to promote NK cell activity and increase effector cell access to lymph node follicles.

Special Translational Considerations

The Window of Vulnerability

Although the understanding of viral latency and proviral persistence is still imperfect, clinical studies seeking to combine immunotherapies with LRAs have begun. However, the leap to translational studies is challenged by the lack of validated metrics and assays that can guide the pathway for clinical development. Detailed virologic, immunologic, and pharmacodynamic assessment of interventions must be made *in vivo*, and such assessments are complicated by the fact that the ultimate efficacy of latency reversal is difficult to quantify without a parallel clearance intervention. Conversely, immunotherapies that might target the latent reservoir cannot be fully tested in the absence of effective latency reversal.

The first challenge is to define the metrics for effective HIV latency reversal. Typically, "more is better," but the most potent current LRAs tested *in vitro* induce cytokine storm and other clinically untenable toxicities. Because immunotherapies are likely to be needed to clear persistent infection, it is rational to define effective LRA activity as activity that induces presentation of a viral protein or antigen in a latently infected cell at a sufficient quantity and for a sufficient length of time to allow immune-mediated clearance. Measurement of rare or low-level HIV-1 protein or peptide production following LRA exposure is currently challenging, although assays detecting antigen at the single-cell level are emerging (Cabrera et al., 2015). A latency clearance assay has been presented (Sung et al., 2015a), seeking to define, in an *ex vivo* assay, the "window of vulnerability" that can be achieved by a selected intervention. However, in its current form, this assay is demanding, has low throughput, and is only semiquantitative. Better assays for this purpose are needed to guide selection of LRA regimens that are sufficient to allow clearance but avoid unacceptable toxicities.

Of Mice and Monkeys

In Vivo Models

Historically, *in vivo* models have proven to be exceptionally informative in virtually all aspects of HIV research. This has also been the case for HIV cure research. *In vivo* models provide a complex substrate that may more closely resemble the human condition than *in vitro* studies and may provide critical information regarding the safety of implementation in humans. Currently, the two models most commonly used to study HIV cure approaches *in vivo* are NHPs and humanized bone marrow/liver/thymus (BLT) mice.

NHPs have been used extensively for HIV cure research. NHPs can be infected with several different types of SIV. Infection results in relatively high initial viral loads and rapid establishment of a long-lasting viral reservoir (Whitney et al., 2018). In addition, the types of experiments that can be conducted in NHPs was expanded by use of HIV/SIV chimeras that permit evaluation of Ab interventions targeted to HIV (Haynes et al., 2019). Several different modalities of ART have been used to suppress viremia in NHPs. Currently, the most commonly used combination includes dolutegravir, tenofovir, and emtricitabine (Nixon et al., 2020). ART is administered daily as a subcutaneous injection that results in a rapid drop of peripheral blood viral RNA to below the level of detection of most commonly used viral load assays (30–60 copies per milliliter of blood). Viral suppression results in establishment of latency, and therapy interruption results in relatively rapid viral rebound. Virtually all current modalities of HIV cure approaches have been evaluated *in vivo* using NHP models. These include stem cell transplantation (SCT), immune modulation/vaccines, gene and cell therapy, as well as induction of latent SIV and destruction of infected cells (Borducchi et al., 2018; Del Prete et al., 2019; Hansen et al., 2011; Lim et al., 2018; Peterson et al., 2018). For the most part, when similar experiments were conducted in humans, the outcomes correlated well between species. Examples of this include the effect of bone marrow transplantation and pre-conditioning, the persistence of transduced cells after transplantation, and induction of plasma viremia and cellular activation after LRA administration.

Rodents are refractory to HIV infection, and therefore they have very limited utility for HIV cure research. However, introduction of human cells and/or tissues renders these "humanized" mice susceptible to HIV infection. Mice can be humanized in several different ways, including hematopoietic SCT (Garcia, 2016). SCT results in robust levels of human cells in peripheral blood and tissues, including human T cells. Importantly, human T cells produced in these models are presumably educated in the mouse thymus and not in the context of human major histocompatibility complex (MHC) molecules (i.e., human leukocyte antigen [HLA]). This limitation was elegantly overcome by the development of humanized BLT mice, where mice are implanted with small pieces of human thymic and liver tissue that give rise to a *bona fide* human thymic organ where T cell precursors can develop into fully functional T cells educated in the context of HLA (Melkus et al., 2006). Because, like NHP, humanized BLT mice can be infected by all physiological routes, infection can be efficiently suppressed by ART, resulting in establishment of HIV latency, and analytical treatment interruption results in viral

rebound (Denton et al., 2008, 2010, 2012; Sun et al., 2007; Wahl et al., 2012, 2015). This and other humanized mouse models have been used extensively to investigate gene/cell therapy, immune modulation, HIV-infected cell killing approaches, HIV silencing approaches, and HIV induction by LRAs (Badamchi-Zadeh et al., 2018; Cheng et al., 2017; Dash et al., 2019; Denton et al., 2014; Zhen et al., 2017). It is in this last area of investigation where the synergy and complementarity between the NHP and humanized mouse models have become most evident. Specifically, in two recent manuscripts, two different HIV induction approaches were independently evaluated in both models (McBrien et al., 2020; Nixon et al., 2020). The results obtained were essentially the same and nicely complemented each other. In the BLT mouse model, it was demonstrated that both latency reversal approaches were effective at inducing systemic production of HIV from resting human CD4+ T cells in the periphery and tissues. In the NHP model, it was demonstrated that these latency reversal approaches can be serially administered, resulting in reproducible induction of SIV in plasma and resting CD4+ T cells from lymph nodes. Both models also provided important information regarding the tolerability of the different LRAs.

It should be made clear that neither NHPs nor BLT mice fully recapitulate the human condition. NHPs provide a robust platform for evaluation of *in vivo* efficacy and toxicity using significantly longer time frames for experimentation and providing larger samples for analysis. BLT mice provide a nimble platform for rapid evaluation of *in vivo* efficacy and potential toxicity using human cells and relevant human viruses. However, both models complement each other in ways that result in robust information useful for determining the suitability of novel approaches to an HIV cure. Moving forward, a new generation of BLT humanized mice that incorporate autologous human non-hematopoietic cells is rapidly providing opportunities for *in vivo* evaluation of novel approaches to HIV cure that require interventions specific for humans (Wahl et al., 2019).

Experimental Medicine Studies

Given the nascent state of HIV cure research, there are limited clinical studies of latency reversal, immunotherapeutic, or combination strategies (Table 1). In addition to the immunological and virological challenges of eradicating HIV, progression into clinical studies has launched discussions regarding the balance of risk versus benefit at a stage when studies involve little or no benefit to the participant within the context of largely translational research.

Because of concerns of ongoing viral replication despite ART, numerous studies of ART intensification were performed without evidence of a decrease in the HIV reservoir or in HIV expression (Rasmussen and Søgaard, 2018). Although still in dispute by a few investigators, overall, studies strongly suggest that ongoing replication does not contribute to maintaining the HIV reservoir in patients suppressed on currently available ART (Bale and Kearney, 2019).

Latency Reversal

Several clinical studies have demonstrated modest induction of viral expression in response to LRAs, with HDACis remaining the most fully characterized. Although HDACis in clinical studies have been well-tolerated and resulted in reproducible increases in cell-associated viral RNA expression (Archin et al., 2012, 2017; Søgaard et al., 2015; Winckelmann et al., 2017; Rasmussen et al., 2014), none have been shown to significantly deplete the viral reservoir. The absence of a reduction in the viral reservoir with LRAs may be due to (1) only partial or "ineffective" reactivation of the overall pool of latently infected cells, (2) inadequate LRA penetration into tissue compartments harboring latent HIV, (3) ineffective clearance of reactivated cells, or a combination of these shortcomings. A variety of other biomolecules are under investigation as LRAs as described, but experience in clinical studies remains limited because of safety concerns related to potential off-target effects.

However, the TLR-9 agonist (MGN1703) was well-tolerated in PLWH on suppressive ART as a twice-weekly subcutaneous injection for 24 weeks (Vibholm et al., 2019). Despite observed increases in HIV-1-specific T cell responses and T cell activation with multiple doses of MGN1703, there were no difference in the time to viral rebound in participants who underwent ART interruption with or without continued MGN1703 dosing (Vibholm et al., 2019). N-803, an IL-15 superagonist, resulted in quantifiable low-level viremia in 2 of 9 participants on suppressive ART, perhaps because of indirect mechanisms (Z. Davis et al., 2018, Conference on Retroviruses and Opportunistic Infections, abstract).

Vaccines

Therapeutic vaccines have been proposed as a method for improving clearance of HIV-infected cells in PLWH suppressed on ART, and the focus has been predominantly on vaccines that induce T cell responses. Although clinical studies of therapeutic HIV vaccines have shown an effect on HIV-specific T cell immunity, the overall response has been disappointing (reviewed in Robinson, 2018), and to date, therapeutic vaccination has not resulted in sustained viral suppression following analytic treatment interruption (B. Mothe et al., 2017, Conference on Retroviruses and Opportunistic Infections, abstract; Sneller et al., 2017).

bnAbs and Other Antibodies

An immunotherapeutic strategy for HIV cure includes passive transfer of NAbs. Several monoclonal NAbs have been shown to reduce viremia in untreated PLWH (Caskey et al., 2015, 2017; Lynch et al., 2015). However, a randomized controlled trial of two infusions of the NAb VRC01 versus placebo in PLWH on suppressive ART showed no difference in the cell-associated HIV RNA/DNA ratio and no effect on low-level viremia (Riddler et al., 2018). As mentioned above, bNAbs have been shown to delay the time to viral rebound in ART-suppressed participants following ATI (Bar et al., 2016; Scheid et al., 2016) but also to select for resistant viral variants. Monoclonal bNAbs clearly have an antiretroviral effect, and dual combination can maintain suppression without resistance emergence (Mendoza et al., 2018). Two participants in this study sustained suppression even after antibody concentration waned, suggesting an additional mechanism of activity beyond direct inhibition. Whether bNAbs with greater potency and breadth than VRC01 will help clear HIV-infected cells is being studied.

Other mAbs used for treatment of other conditions have also been explored, including a mAb against $\alpha4\beta7$ integrin, which

enables homing of T lymphocytes to the gut. Preclinical studies of the anti-α4β7 mAb suggested a role in preventing SIV infection and preserving CD4+ T cells in gut-associated lymphoid tissue (GALT) and peripheral blood as well as in limiting SIV infection in GALT. However, administration of the anti-α4β7 mAb to suppressed PLWH did not affect time to viral rebound during ATI (Sneller et al., 2019).

Immune Checkpoint Inhibitors

Immune checkpoint inhibitors (ICIs) have revolutionized cancer therapy by reversing cancer-related immune dysfunction associated with specific malignancies. HIV-specific T cell exhaustion persists even on effective ART and may be a barrier to HIV cure. In addition, CD4+ T cells expressing immune checkpoint markers are enriched for latent HIV (Banga et al., 2016; Chomont et al., 2009; Fromentin et al., 2016). Therefore, ICIs could provide a strategy for reversing HIV-associated immune dysfunction and targeting cells with latent HIV-1. There has been one clinical study of ICIs in PLWH on ART without malignancy, in which a single low-dose infusion of an anti-PD-L1 mAb (BMS-936559) appeared to enhance HIV-1-specific immune responses in 2 of 6 participants (Gay et al., 2017).

The role of immune checkpoint pathways in maintaining latency has been suggested in a case report of a PLWH on ART, with a 20-fold increase in cell-associated HIV RNA in CD4+ T cells observed following multiple infusions of anti-CTLA-4 (ipilimumab) (Wightman et al., 2015). The same individual later received a single infusion of nivolumab for metastatic melanoma treatment, with a 24-fold significant increase in ca-HIV RNA post-infusion, both suggesting *in vivo* latency reversal following ICI administration. However, anti-HIV immune enhancement and LRA activity are not universally observed, and in otherwise healthy PLWH on effective ART, the relatively frequent and sometimes severe autoimmune adverse events associated with ICIs may make this approach unacceptable.

Additional adaption of immunotherapy advances in cancer treatment to strategies for HIV cure, bolstered by the two cases of clinical cure following SCT for cancer treatment (R.K. Gupta et al., 2019, Conference on Retroviruses and Opportunistic Infections, abstract), includes adoptive T cell therapy, gene editing, bispecific antibodies and anti-HIV CAR T cells. Although earlier studies of adoptive T cell therapy for HIV-1 established their safety (reviewed in Lam and Bollard, 2013), antiviral efficacy was transient, in part because of reliance on monoclonal T cells, extensive *in vitro* expansion resulting in a potentially exhausted phenotype, and infusion of T cells into viremic untreated patients. When applied in the setting of ART suppression, HIV-specific T cells persisted in the blood and were capable of homing to rectal tissue, but virologic outcomes were not reported (Chapuis et al., 2011). Previous studies also examined infusing T cells specific for a single HLA-restricted epitope, either by clonal selection or introducing an artificial, high-affinity TCR for the HLA-A2 Gag epitope SL9 (Varela-Rohena et al., 2008). Infused T cell clones showed little persistence and no clear long-term reduction in viral load. More recently, infusions of *ex vivo* polyclonal HIV-specific T cells targeting multiple HIV epitopes were safe and increased CD8+ T cell-mediated antiviral activity in 2 of 6 participants but did not increase the overall frequency of HIV-specific T cells, likely because of the low dose employed (Sung et al., 2018). *Ex vivo* site-specific modification of the CCR-5 gene in autologous CD4+ cells using zinc-finger nuclease with re-infusion in PLWH on ART was safe and resulted in HIV RNA suppression in 1 of 4 participants who interrupted ART (Tebas et al., 2014). Studies employing gene editing in stem cells for PLWH undergoing SCT for malignancy are ongoing.

Combination Studies

Because pilot studies of latency reversal and pilot studies of enhancement of HIV clearance mechanisms have now demonstrated safety, study of the combination of these two interventions may now proceed. Results from clinical studies combining these two strategies are limited. In a single-arm trial of romidepsin in combination with an adjuvant vaccine, there was lack of HIV-1 reactivation in all participants following romidepsin administration and no effect on the time to viral rebound with an ATI (Leth et al., 2016). A randomized controlled trial combining latency reversal with an HIV vaccine enrolled participants treated within 4 weeks of diagnosis with primary HIV infection who received prime vaccination with ChAdV63.HIVconsv and MVA.HIVconsv boost 8 weeks later, followed by 10 doses of vorinostat every 3 days (Fidler et al., 2020). No reduction in the viral reservoir was observed, as measured by viral outgrowth between weeks 16 and 18 post-randomization, despite significantly higher HIV-specific CD4+ T cell responses and functional CD8+ T cell responses in the intervention versus the ART-only arm. In this population, treated for a relatively short period of time after initial infection, the natural decay of persistent HIV DNA seen in early ART may have obscured a weak effect of the interventions. Initial reports of pilot studies employing similar approaches have also failed to achieve a measurable depletion of latent, persistent infection (Gay et al., 2020; B. Mothe et al., 2017, Conference on Retroviruses and Opportunistic Infections, abstract).

In sum, several clinical studies of HIV cure have shown some ability to enhance HIV-specific immune responses without an associated effect on the viral reservoir or viral control in the absence of ART. More potent LRAs are needed to more effectively reactivate latent HIV. Whether any of the currently available immunotherapeutic strategies, in isolation or in combination, could substantially deplete the pool of latently infected cells induced to express the virus remains unanswered.

Toward an HIV Cure in the Fifth Decade of AIDS

Eradication of infection in PLWH is still not achievable at any scale. But now, in the fifth decade of the AIDS pandemic, we mark more than 10 years of scientific effort refocused toward the goal of viral eradication. Increasingly, tools to approach this goal are emerging. As the understanding of the many mechanisms of viral persistence grows, novel approaches to disrupt and target latency are advancing toward clinical testing.

Advances in the use of HIV antibodies and HIV vaccine development may also be employed to enlist the body's own defenses in recognition and clearance of infected cells. When these barriers are breached, we may discover additional cellular reservoirs of infection and mechanisms of persistence that

require alternate or combinatorial therapeutic approaches. The progress made so far in deciphering HIV pathogenesis and developing treatment strategies gives hope that eradication of established HIV infection is an attainable goal.

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REFERENCES

Abrahams, M.R., Joseph, S.B., Garrett, N., Tyers, L., Moeser, M., Archin, N., Council, O.D., Matten, D., Zhou, S., Doolabh, D., et al. (2019). The replication-competent HIV-1 latent reservoir is primarily established near the time of therapy initiation. Sci. Transl. Med. *11*.

Abreu, C.M., Veenhuis, R.T., Avalos, C.R., Graham, S., Parrilla, D.R., Ferreira, E.A., Queen, S.E., Shirk, E.N., Bullock, B.T., Li, M., et al. (2019). Myeloid and CD4 T Cells Comprise the Latent Reservoir in Antiretroviral Therapy-Suppressed SIVmac251-Infected Macaques. MBio *10*.

Anderson, J.L., Khoury, G., Fromentin, R., Solomon, A., Chomont, N., Sinclair, E., Milush, J.M., Hartogensis, W., Bacchetti, P., Roche, M., et al. (2020). Human Immunodeficiency Virus (HIV)-Infected CCR6+ Rectal CD4+ T Cells and HIV Persistence On Antiretroviral Therapy. J. Infect. Dis. *221*, 744–755.

Archin, N.M., Liberty, A.L., Kashuba, A.D., Choudhary, S.K., Kuruc, J.D., Crooks, A.M., Parker, D.C., Anderson, E.M., Kearney, M.F., Strain, M.C., et al. (2012). Administration of vorinostat disrupts HIV-1 latency in patients on antiretroviral therapy. Nature *487*, 482–485.

Archin, N.M., Kirchherr, J.L., Sung, J.A., Clutton, G., Sholtis, K., Xu, Y., Allard, B., Stuelke, E., Kashuba, A.D., Kuruc, J.D., et al. (2017). Interval dosing with the HDAC inhibitor vorinostat effectively reverses HIV latency. J. Clin. Invest. *127*, 3126–3135.

Avalos, C.R., Abreu, C.M., Queen, S.E., Li, M., Price, S., Shirk, E.N., Engle, E.L., Forsyth, E., Bullock, B.T., Mac Gabhann, F., et al. (2017). Brain Macrophages in Simian Immunodeficiency Virus-Infected, Antiretroviral-Suppressed Macaques: a Functional Latent Reservoir. MBio *8*.

Badamchi-Zadeh, A., Tartaglia, L.J., Abbink, P., Bricault, C.A., Liu, P.T., Boyd, M., Kirilova, M., Mercado, N.B., Nanayakkara, O.S., Vrbanac, V.D., et al. (2018). Therapeutic Efficacy of Vectored PGT121 Gene Delivery in HIV-1-Infected Humanized Mice. J. Virol. *92*.

Bailey, J.R., Sedaghat, A.R., Kieffer, T., Brennan, T., Lee, P.K., Wind-Rotolo, M., Haggerty, C.M., Kamireddi, A.R., Liu, Y., Lee, J., et al. (2006). Residual human immunodeficiency virus type 1 viremia in some patients on antiretroviral therapy is dominated by a small number of invariant clones rarely found in circulating CD4+ T cells. J. Virol. *80*, 6441–6457.

Bale, M.J., and Kearney, M.F. (2019). Review: HIV-1 phylogeny during suppressive antiretroviral therapy. Curr. Opin. HIV AIDS *14*, 188–193.

Banga, R., Procopio, F.A., Noto, A., Pollakis, G., Cavassini, M., Ohmiti, K., Corpataux, J.M., de Leval, L., Pantaleo, G., and Perreau, M. (2016). PD-1(+) and follicular helper T cells are responsible for persistent HIV-1 transcription in treated aviremic individuals. Nat. Med. *22*, 754–761.

Bar, K.J., Sneller, M.C., Harrison, L.J., Justement, J.S., Overton, E.T., Petrone, M.E., Salantes, D.B., Seamon, C.A., Scheinfeld, B., Kwan, R.W., et al. (2016). Effect of HIV Antibody VRC01 on Viral Rebound after Treatment Interruption. N. Engl. J. Med. *375*, 2037–2050.

Boehm, D., and Ott, M. (2017). Host Methyltransferases and Demethylases: Potential New Epigenetic Targets for HIV Cure Strategies and Beyond. AIDS Res. Hum. Retroviruses *33* (S1), S8–S22.

Boehm, D., Conrad, R.J., and Ott, M. (2013). Bromodomain proteins in HIV infection. Viruses *5*, 1571–1586.

Borducchi, E.N., Liu, J., Nkolola, J.P., Cadena, A.M., Yu, W.H., Fischinger, S., Broge, T., Abbink, P., Mercado, N.B., Chandrashekar, A., et al. (2018). Antibody and TLR7 agonist delay viral rebound in SHIV-infected monkeys. Nature *563*, 360–364.

Bradley, T., Ferrari, G., Haynes, B.F., Margolis, D.M., and Browne, E.P. (2018). Single-Cell Analysis of Quiescent HIV Infection Reveals Host Transcriptional Profiles that Regulate Proviral Latency. Cell Rep. *25*, 107–117.e3.

Brodin, J., Zanini, F., Thebo, L., Lanz, C., Bratt, G., Neher, R.A., and Albert, J. (2016). Establishment and stability of the latent HIV-1 DNA reservoir. eLife *5*, e18889.

Bronnimann, M.P., Skinner, P.J., and Connick, E. (2018). The B-Cell Follicle in HIV Infection: Barrier to a Cure. Front. Immunol. *9*, 20.

Bruner, K.M., Murray, A.J., Pollack, R.A., Soliman, M.G., Laskey, S.B., Capoferri, A.A., Lai, J., Strain, M.C., Lada, S.M., Hoh, R., et al. (2016). Defective proviruses rapidly accumulate during acute HIV-1 infection. Nat. Med. *22*, 1043–1049.

Bruner, K.M., Wang, Z., Simonetti, F.R., Bender, A.M., Kwon, K.J., Sengupta, S., Fray, E.J., Beg, S.A., Antar, A.A.R., Jenike, K.M., et al. (2019). A quantitative approach for measuring the reservoir of latent HIV-1 proviruses. Nature *566*, 120–125.

Bui, J.K., Sobolewski, M.D., Keele, B.F., Spindler, J., Musick, A., Wiegand, A., Luke, B.T., Shao, W., Hughes, S.H., Coffin, J.M., et al. (2017). Proviruses with identical sequences comprise a large fraction of the replication-competent HIV reservoir. PLoS Pathog. *13*, e1006283.

Buzon, M.J., Sun, H., Li, C., Shaw, A., Seiss, K., Ouyang, Z., Martin-Gayo, E., Leng, J., Henrich, T.J., Li, J.Z., et al. (2014). HIV-1 persistence in CD4+ T cells with stem cell-like properties. Nat. Med. *20*, 139–142.

Cabrera, C., Chang, L., Stone, M., Busch, M., and Wilson, D.H. (2015). Rapid, Fully Automated Digital Immunoassay for p24 Protein with the Sensitivity of Nucleic Acid Amplification for Detecting Acute HIV Infection. Clin. Chem. *61*, 1372–1380.

Caskey, M., Klein, F., Lorenzi, J.C., Seaman, M.S., West, A.P., Jr., Buckley, N., Kremer, G., Nogueira, L., Braunschweig, M., Scheid, J.F., et al. (2015). Viraemia suppressed in HIV-1-infected humans by broadly neutralizing antibody 3BNC117. Nature *522*, 487–491.

Caskey, M., Schoofs, T., Gruell, H., Settler, A., Karagounis, T., Kreider, E.F., Murrell, B., Pfeifer, N., Nogueira, L., Oliveira, T.Y., et al. (2017). Antibody 10-1074 suppresses viremia in HIV-1-infected individuals. Nat. Med. *23*, 185–191.

Chapuis, A.G., Casper, C., Kuntz, S., Zhu, J., Tjernlund, A., Diem, K., Turtle, C.J., Cigal, M.L., Velez, R., Riddell, S., et al. (2011). HIV-specific CD8+ T cells from HIV+ individuals receiving HAART can be expanded ex vivo to augment systemic and mucosal immunity in vivo. Blood *117*, 5391–5402.

Cheng, L., Yu, H., Li, G., Li, F., Ma, J., Li, J., Chi, L., Zhang, L., and Su, L. (2017). Type I interferons suppress viral replication but contribute to T cell depletion and dysfunction during chronic HIV-1 infection. JCI Insight *2*.

Chomont, N., El-Far, M., Ancuta, P., Trautmann, L., Procopio, F.A., Yassine-Diab, B., Boucher, G., Boulassel, M.R., Ghattas, G., Brenchley, J.M., et al. (2009). HIV reservoir size and persistence are driven by T cell survival and homeostatic proliferation. Nat. Med. *15*, 893–900.

Chun, T.W., Finzi, D., Margolick, J., Chadwick, K., Schwartz, D., and Siliciano, R.F. (1995). In vivo fate of HIV-1-infected T cells: quantitative analysis of the transition to stable latency. Nat. Med. *1*, 1284–1290.

Chun, T.W., Carruth, L., Finzi, D., Shen, X., DiGiuseppe, J.A., Taylor, H., Hermankova, M., Chadwick, K., Margolick, J., Quinn, T.C., et al. (1997a). Quantification of latent tissue reservoirs and total body viral load in HIV-1 infection. Nature *387*, 183–188.

Chun, T.W., Stuyver, L., Mizell, S.B., Ehler, L.A., Mican, J.A., Baseler, M., Lloyd, A.L., Nowak, M.A., and Fauci, A.S. (1997b). Presence of an inducible HIV-1 latent reservoir during highly active antiretroviral therapy. Proc. Natl. Acad. Sci. USA *94*, 13193–13197.

Clutton, G.T., and Jones, R.B. (2018). Diverse Impacts of HIV Latency-Reversing Agents on CD8+ T-Cell Function: Implications for HIV Cure. Front. Immunol. *9*, 1452.

Conrad, R.J., Fozouni, P., Thomas, S., Sy, H., Zhang, Q., Zhou, M.-M., and Ott, M. (2017). The Short Isoform of BRD4 Promotes HIV-1 Latency by Engaging Repressive SWI/SNF Chromatin-Remodeling Complexes. Mol. Cell *67*, 1001–1012.e6.

Crooks, A.M., Bateson, R., Cope, A.B., Dahl, N.P., Griggs, M.K., Kuruc, J.D., Gay, C.L., Eron, J.J., Margolis, D.M., Bosch, R.J., and Archin, N.M. (2015). Precise quantitation of the latent HIV-1 reservoir: implications for eradication strategies. J. Infect. Dis. *212*, 1361–1365.

Dash, P.K., Kaminski, R., Bella, R., Su, H., Mathews, S., Ahooyi, T.M., Chen, C., Mancuso, P., Sariyer, R., Ferrante, P., et al. (2019). Sequential LASER ART and CRISPR Treatments Eliminate HIV-1 in a Subset of Infected Humanized Mice. Nat. Commun. *10*, 2753.

Del Prete, G.Q., Alvord, W.G., Li, Y., Deleage, C., Nag, M., Oswald, K., Thomas, J.A., Pyle, C., Bosche, W.J., Coalter, V., et al. (2019). TLR7 agonist administration to SIV-infected macaques receiving early initiated cART does not induce plasma viremia. JCI Insight *4*.

Deng, K., Pertea, M., Rongvaux, A., Wang, L., Durand, C.M., Ghiaur, G., Lai, J., McHugh, H.L., Hao, H., Zhang, H., et al. (2015). Broad CTL response is required to clear latent HIV-1 due to dominance of escape mutations. Nature *517*, 381–385.

Denton, P.W., Estes, J.D., Sun, Z., Othieno, F.A., Wei, B.L., Wege, A.K., Powell, D.A., Payne, D., Haase, A.T., and Garcia, J.V. (2008). Antiretroviral preexposure prophylaxis prevents vaginal transmission of HIV-1 in humanized BLT mice. PLoS Med. *5*, e16.

Denton, P.W., Krisko, J.F., Powell, D.A., Mathias, M., Kwak, Y.T., Martinez-Torres, F., Zou, W., Payne, D.A., Estes, J.D., and Garcia, J.V. (2010). Systemic administration of antiretrovirals prior to exposure prevents rectal and intravenous HIV-1 transmission in humanized BLT mice. PLoS ONE *5*, e8829.

Denton, P.W., Olesen, R., Choudhary, S.K., Archin, N.M., Wahl, A., Swanson, M.D., Chateau, M., Nochi, T., Krisko, J.F., Spagnuolo, R.A., et al. (2012). Generation of HIV latency in humanized BLT mice. J. Virol. *86*, 630–634.

Denton, P.W., Long, J.M., Wietgrefe, S.W., Sykes, C., Spagnuolo, R.A., Snyder, O.D., Perkey, K., Archin, N.M., Choudhary, S.K., Yang, K., et al. (2014). Targeted cytotoxic therapy kills persisting HIV infected cells during ART. PLoS Pathog. *10*, e1003872.

Eisinger, R.W., and Fauci, A.S. (2018). Ending the HIV/AIDS Pandemic[1]. Emerg. Infect. Dis. *24*, 413–416.

Estes, J.D., Kityo, C., Ssali, F., Swainson, L., Makamdop, K.N., Del Prete, G.Q., Deeks, S.G., Luciw, P.A., Chipman, J.G., Beilman, G.J., et al. (2017). Defining total-body AIDS-virus burden with implications for curative strategies. Nat. Med. *23*, 1271–1276.

Farber, D.L., Yudanin, N.A., and Restifo, N.P. (2014). Human memory T cells: generation, compartmentalization and homeostasis. Nat. Rev. Immunol. *14*, 24–35.

Ferrari, G., Haynes, B.F., Koenig, S., Nordstrom, J.L., Margolis, D.M., and Tomaras, G.D. (2016). Envelope-specific antibodies and antibody-derived molecules for treating and curing HIV infection. Nat. Rev. Drug Discov. *15*, 823–834.

Fidler, S., Stohr, W., Pace, M., Dorrell, L., Lever, A., Pett, S., Kinloch-de Loes, S., Fox, J., Clarke, A., Nelson, M., et al. (2020). Antiretroviral therapy alone versus antiretroviral therapy with a kick and kill approach, on measures of the HIV reservoir in participants with recent HIV infection (the RIVER trial): a phase 2, randomised trial. Lancet. Published online February 18, 2018. https://doi.org/10.1016/S0140-6736(19)32990-3.

Finzi, D., Hermankova, M., Pierson, T., Carruth, L.M., Buck, C., Chaisson, R.E., Quinn, T.C., Chadwick, K., Margolick, J., Brookmeyer, R., et al. (1997). Identification of a reservoir for HIV-1 in patients on highly active antiretroviral therapy. Science *278*, 1295–1300.

Fisher, L., Zinter, M., Stanfield-Oakley, S., Carpp, L.N., Edwards, R.W., Denny, T., Moodie, Z., Laher, F., Bekker, L.-G., McElrath, M.J., et al. (2019). Vaccine-Induced Antibodies Mediate Higher Antibody-Dependent Cellular Cytotoxicity After Interleukin-15 Pretreatment of Natural Killer Effector Cells. Front. Immunol. *10*, 2741.

Fromentin, R., Bakeman, W., Lawani, M.B., Khoury, G., Hartogensis, W., DaFonseca, S., Killian, M., Epling, L., Hoh, R., Sinclair, E., et al. (2016). CD4+ T Cells Expressing PD-1, TIGIT and LAG-3 Contribute to HIV Persistence during ART. PLoS Pathog. *12*, e1005761.

Ganor, Y., Real, F., Sennepin, A., Dutertre, C.A., Prevedel, L., Xu, L., Tudor, D., Charmeteau, B., Couedel-Courteille, A., Marion, S., et al. (2019). HIV-1 reservoirs in urethral macrophages of patients under suppressive antiretroviral therapy. Nat. Microbiol. *4*, 633–644.

Garcia, J.V. (2016). In vivo platforms for analysis of HIV persistence and eradication. J. Clin. Invest. *126*, 424–431.

Garrido, C., Abad-Fernandez, M., Tuyishime, M., Pollara, J.J., Ferrari, G., Soriano-Sarabia, N., and Margolis, D.M. (2018). Interleukin-15-Stimulated Natural Killer Cells Clear HIV-1-Infected Cells following Latency Reversal *Ex Vivo*. J. Virol. *92*.

Gay, C.L., Bosch, R.J., Ritz, J., Hataye, J.M., Aga, E., Tressler, R.L., Mason, S.W., Hwang, C.K., Grasela, D.M., Ray, N., et al.; AIDS Clinical Trials 5326 Study Team (2017). Clinical Trial of the Anti-PD-L1 Antibody BMS-936559 in HIV-1 Infected Participants on Suppressive Antiretroviral Therapy. J. Infect. Dis. *215*, 1725–1733.

Gay, C.L., Kuruc, J.D., Falcinelli, S.D., Warren, J.A., Reifeis, S.A., Kirchherr, J.L., James, K.S., Dewey, M.G., Helms, A., Allard, B., et al. (2020). Assessing the impact of AGS-004, a dendritic cell-based immunotherapy, and vorinostat on persistent HIV-1 Infection. Sci. Rep. *10*, 5134.

Goonetilleke, N., Liu, M.K., Salazar-Gonzalez, J.F., Ferrari, G., Giorgi, E., Ganusov, V.V., Keele, B.F., Learn, G.H., Turnbull, E.L., Salazar, M.G., et al.; CHAVI Clinical Core B (2009). The first T cell response to transmitted/founder virus contributes to the control of acute viremia in HIV-1 infection. J. Exp. Med. *206*, 1253–1272.

Goonetilleke, N., Clutton, G., Swanstrom, R., and Joseph, S.B. (2019). Blocking Formation of the Stable HIV Reservoir: A New Perspective for HIV-1 Cure. Front. Immunol. *10*, 1966.

Gosselin, A., Wiche Salinas, T.R., Planas, D., Wacleche, V.S., Zhang, Y., Fromentin, R., Chomont, N., Cohen, E.A., Shacklett, B., Mehraj, V., et al. (2017). HIV persists in CCR6+CD4+ T cells from colon and blood during antiretroviral therapy. AIDS *31*, 35–48.

Gulick, R.M., and Flexner, C. (2019). Long-Acting HIV Drugs for Treatment and Prevention. Annu. Rev. Med. *70*, 137–150.

Gutiérrez, C., Serrano-Villar, S., Madrid-Elena, N., Pérez-Elías, M.J., Martín, M.E., Barbas, C., Ruipérez, J., Muñoz, E., Muñoz-Fernández, M.A., Castor, T., and Moreno, S. (2016). Bryostatin-1 for latent virus reactivation in HIV-infected patients on antiretroviral therapy. AIDS *30*, 1385–1392.

Hamer, D.H. (2004). Can HIV be Cured? Mechanisms of HIV persistence and strategies to combat it. Curr. HIV Res. *2*, 99–111.

Hansen, S.G., Ford, J.C., Lewis, M.S., Ventura, A.B., Hughes, C.M., Coyne-Johnson, L., Whizin, N., Oswald, K., Shoemaker, R., Swanson, T., et al. (2011). Profound early control of highly pathogenic SIV by an effector memory T-cell vaccine. Nature *473*, 523–527.

Haynes, B.F., Burton, D.R., and Mascola, J.R. (2019). Multiple roles for HIV broadly neutralizing antibodies. Sci. Transl. Med. *11*.

Henrich, T.J., Hatano, H., Bacon, O., Hogan, L.E., Rutishauser, R., Hill, A., Kearney, M.F., Anderson, E.M., Buchbinder, S.P., Cohen, S.E., et al. (2017). HIV-1 persistence following extremely early initiation of antiretroviral therapy (ART) during acute HIV-1 infection: An observational study. PLoS Med. *14*, e1002417.

Hiener, B., Horsburgh, B.A., Eden, J.S., Barton, K., Schlub, T.E., Lee, E., von Stockenstrom, S., Odevall, L., Milush, J.M., Liegler, T., et al. (2017).

Identification of Genetically Intact HIV-1 Proviruses in Specific CD4+ T Cells from Effectively Treated Participants. Cell Rep. *21*, 813–822.

Ho, Y.-C., Shan, L., Hosmane, N.N., Wang, J., Laskey, S.B., Rosenbloom, D.I.S., Lai, J., Blankson, J.N., Siliciano, J.D., and Siliciano, R.F. (2013). Replication-competent noninduced proviruses in the latent reservoir increase barrier to HIV-1 cure. Cell *155*, 540–551.

Honeycutt, J.B., Thayer, W.O., Baker, C.E., Ribeiro, R.M., Lada, S.M., Cao, Y., Cleary, R.A., Hudgens, M.G., Richman, D.D., and Garcia, J.V. (2017). HIV persistence in tissue macrophages of humanized myeloid-only mice during antiretroviral therapy. Nat. Med. *23*, 638–643.

Hosmane, N.N., Kwon, K.J., Bruner, K.M., Capoferri, A.A., Beg, S., Rosenbloom, D.I., Keele, B.F., Ho, Y.C., Siliciano, J.D., and Siliciano, R.F. (2017). Proliferation of latently infected CD4+ T cells carrying replication-competent HIV-1: Potential role in latent reservoir dynamics. J. Exp. Med. *214*, 959–972.

Houzet, L., Matusali, G., and Dejucq-Rainsford, N. (2014). Origins of HIV-infected leukocytes and virions in semen. J. Infect. Dis. *210* (*Suppl 3*), S622–S630.

Jenuwein, T., and Allis, C.D. (2001). Translating the histone code. Science *293*, 1074–1080.

Jiang, G., and Dandekar, S. (2015). Targeting NF-κB signaling with protein kinase C agonists as an emerging strategy for combating HIV latency. AIDS Res. Hum. Retroviruses *31*, 4–12.

Jiang, G., Nguyen, D., Archin, N.M., Yukl, S.A., Méndez-Lagares, G., Tang, Y., Elsheikh, M.M., Thompson, G.R., 3rd, Hartigan-O'Connor, D.J., Margolis, D.M., et al. (2018). HIV latency is reversed by ACSS2-driven histone crotonylation. J. Clin. Invest. *128*, 1190–1198.

Jiang, G., Maverakis, E., Cheng, M.Y., Elsheikh, M.M., Deleage, C., Méndez-Lagares, G., Shimoda, M., Yukl, S.A., Hartigan-O'Connor, D.J., Thompson, G.R., 3rd., et al. (2019). Disruption of latent HIV in vivo during the clearance of actinic keratosis by ingenol mebutate. JCI Insight *4*.

Joseph, S.B., and Swanstrom, R. (2018). The evolution of HIV-1 entry phenotypes as a guide to changing target cells. J. Leukoc. Biol. *103*, 421–431.

Joseph, S.B., Trunfio, M., Kincer, L.P., Calcagno, A., and Price, R.W. (2019). What can characterization of cerebrospinal fluid escape populations teach us about viral reservoirs in the central nervous system? AIDS *33* (*Suppl 2*), S171–S179.

Katlama, C., Lambert-Niclot, S., Assoumou, L., Papagno, L., Lecardonnel, F., Zoorob, R., Tambussi, G., Clotet, B., Youle, M., Achenbach, C.J., et al.; ERAMune-01 study team (2016). Treatment intensification followed by interleukin-7 reactivates HIV without reducing total HIV DNA: a randomized trial. AIDS *30*, 221–230.

Kim, J.H., Excler, J.L., and Michael, N.L. (2015). Lessons from the RV144 Thai phase III HIV-1 vaccine trial and the search for correlates of protection. Annu. Rev. Med. *66*, 423–437.

Kulpa, D.A., Talla, A., Brehm, J.H., Ribeiro, S.P., Yuan, S., Bebin-Blackwell, A.G., Miller, M., Barnard, R., Deeks, S.G., Hazuda, D., et al. (2019). Differentiation into an Effector Memory Phenotype Potentiates HIV-1 Latency Reversal in CD4+ T Cells. J. Virol. *93*.

Lam, S., and Bollard, C. (2013). T-cell therapies for HIV. Immunotherapy *5*, 407–414.

Lamers, S.L., Rose, R., Maidji, E., Agsalda-Garcia, M., Nolan, D.J., Fogel, G.B., Salemi, M., Garcia, D.L., Bracci, P., Yong, W., et al. (2016). HIV DNA Is Frequently Present within Pathologic Tissues Evaluated at Autopsy from Combined Antiretroviral Therapy-Treated Patients with Undetectable Viral Loads. J. Virol. *90*, 8968–8983.

Lehrman, G., Ylisastigui, L., Bosch, R.J., and Margolis, D.M. (2004). Interleukin-7 induces HIV type 1 outgrowth from peripheral resting CD4+ T cells. J. Acquir. Immune Defic. Syndr. *36*, 1103–1104.

Leth, S., Schleimann, M.H., Nissen, S.K., Højen, J.F., Olesen, R., Graversen, M.E., Jørgensen, S., Kjær, A.S., Denton, P.W., Mørk, A., et al. (2016). Combined effect of Vacc-4x, recombinant human granulocyte macrophage colony-stimulating factor vaccination, and romidepsin on the HIV-1 reservoir (REDUC): a single-arm, phase 1B/2A trial. Lancet HIV *3*, e463–e472.

Lim, S.Y., Osuna, C.E., Hraber, P.T., Hesselgesser, J., Gerold, J.M., Barnes, T.L., Sanisetty, S., Seaman, M.S., Lewis, M.G., Geleziunas, R., et al. (2018). TLR7 agonists induce transient viremia and reduce the viral reservoir in SIV-infected rhesus macaques on antiretroviral therapy. Sci. Transl. Med. *10*.

Luzuriaga, K., Gay, H., Ziemniak, C., Sanborn, K.B., Somasundaran, M., Rainwater-Lovett, K., Mellors, J.W., Rosenbloom, D., and Persaud, D. (2015). Viremic relapse after HIV-1 remission in a perinatally infected child. N. Engl. J. Med. *372*, 786–788.

Lynch, R.M., Boritz, E., Coates, E.E., DeZure, A., Madden, P., Costner, P., Enama, M.E., Plummer, S., Holman, L., Hendel, C.S., et al.; VRC 601 Study Team (2015). Virologic effects of broadly neutralizing antibody VRC01 administration during chronic HIV-1 infection. Sci. Transl. Med. *7*, 319ra206.

Macedo, A.B., Novis, C.L., and Bosque, A. (2019). Targeting Cellular and Tissue HIV Reservoirs With Toll-Like Receptor Agonists. Front. Immunol. *10*, 2450.

Maldarelli, F., Wu, X., Su, L., Simonetti, F.R., Shao, W., Hill, S., Spindler, J., Ferris, A.L., Mellors, J.W., Kearney, M.F., et al. (2014). HIV latency. Specific HIV integration sites are linked to clonal expansion and persistence of infected cells. Science *345*, 179–183.

Marsden, M.D., Loy, B.A., Wu, X., Ramirez, C.M., Schrier, A.J., Murray, D., Shimizu, A., Ryckbosch, S.M., Near, K.E., Chun, T.W., et al. (2017). In vivo activation of latent HIV with a synthetic bryostatin analog effects both latent cell "kick" and "kill" in strategy for virus eradication. PLoS Pathog. *13*, e1006575.

Mbonye, U., and Karn, J. (2014). Transcriptional control of HIV latency: cellular signaling pathways, epigenetics, happenstance and the hope for a cure. Virology *454-455*, 328–339.

McBrien, J.B., Mavigner, M., Franchitti, L., Smith, S.A., White, E., Tharp, G.K., Walum, H., Busman-Suhay, K., Aguilera-Sandoval, C.R., Thayer, W.O., et al. (2020). Robust and persistent reactivation of SIV and HIV by N-803 and depletion of CD8(+) cells. Nature *578*, 154–159.

Meier, U.C., Klenerman, P., Griffin, P., James, W., Köppe, B., Larder, B., McMichael, A., and Phillips, R. (1995). Cytotoxic T lymphocyte lysis inhibited by viable HIV mutants. Science *270*, 1360–1362.

Melkus, M.W., Estes, J.D., Padgett-Thomas, A., Gatlin, J., Denton, P.W., Othieno, F.A., Wege, A.K., Haase, A.T., and Garcia, J.V. (2006). Humanized mice mount specific adaptive and innate immune responses to EBV and TSST-1. Nat. Med. *12*, 1316–1322.

Mendoza, P., Gruell, H., Nogueira, L., Pai, J.A., Butler, A.L., Millard, K., Lehmann, C., Suárez, I., Oliveira, T.Y., Lorenzi, J.C.C., et al. (2018). Combination therapy with anti-HIV-1 antibodies maintains viral suppression. Nature *561*, 479–484.

Moog, C., Dereuddre-Bosquet, N., Teillaud, J.-L., Biedma, M.E., Holl, V., Van Ham, G., Heyndrickx, L., Van Dorsselaer, A., Katinger, D., Vcelar, B., et al. (2014). Protective effect of vaginal application of neutralizing and nonneutralizing inhibitory antibodies against vaginal SHIV challenge in macaques. Mucosal Immunol. *7*, 46–56.

Nguyen, K., Das, B., Dobrowolski, C., and Karn, J. (2017). Multiple Histone Lysine Methyltransferases Are Required for the Establishment and Maintenance of HIV-1 Latency. MBio *8*.

Nixon, C.C., Mavigner, M., Sampey, G.C., Brooks, A.D., Spagnuolo, R.A., Irlbeck, D.M., Mattingly, C., Ho, P.T., Schoof, N., Cammon, C.G., et al. (2020). Systemic HIV and SIV latency reversal via non-canonical NF-κB signalling in vivo. Nature *578*, 160–165.

Pache, L., Dutra, M.S., Spivak, A.M., Marlett, J.M., Murry, J.P., Hwang, Y., Maestre, A.M., Manganaro, L., Vamos, M., Teriete, P., et al. (2015). BIRC2/cIAP1 Is a Negative Regulator of HIV-1 Transcription and Can Be Targeted by Smac Mimetics to Promote Reversal of Viral Latency. Cell Host Microbe *18*, 345–353.

Pallikkuth, S., Sharkey, M., Babic, D.Z., Gupta, S., Stone, G.W., Fischl, M.A., Stevenson, M., and Pahwa, S. (2015). Peripheral T Follicular Helper Cells Are the Major HIV Reservoir within Central Memory CD4 T Cells in Peripheral Blood from Chronically HIV-Infected Individuals on Combination Antiretroviral Therapy. J. Virol. *90*, 2718–2728.

Pankau, M.D., Reeves, D.B., Harkins, E., Ronen, K., Jaoko, W., Mandaliya, K., Graham, S.M., McClelland, R.S., Matsen Iv, F.A., Schiffer, J.T., et al. (2020). Dynamics of HIV DNA reservoir seeding in a cohort of superinfected Kenyan women. PLoS Pathog. *16*, e1008286.

Pardons, M., Fromentin, R., Pagliuzza, A., Routy, J.P., and Chomont, N. (2019). Latency-Reversing Agents Induce Differential Responses in Distinct Memory CD4 T Cell Subsets in Individuals on Antiretroviral Therapy. Cell Rep. *29*, 2783–2795.e5.

Pegu, A., Asokan, M., Wu, L., Wang, K., Hataye, J., Casazza, J.P., Guo, X., Shi, W., Georgiev, I., Zhou, T., et al. (2015). Activation and lysis of human CD4 cells latently infected with HIV-1. Nat. Commun. *6*, 8447.

Peterson, C.W., Wang, J., Deleage, C., Reddy, S., Kaur, J., Polacino, P., Reik, A., Huang, M.L., Jerome, K.R., Hu, S.L., et al. (2018). Differential impact of transplantation on peripheral and tissue-associated viral reservoirs: Implications for HIV gene therapy. PLoS Pathog. *14*, e1006956.

Pollara, J., Bonsignori, M., Moody, M.A., Pazgier, M., Haynes, B.F., and Ferrari, G. (2013). Epitope Specificity of Human Immunodeficiency Virus-1 Antibody Dependent Cellular Cytotoxicity [ADCC] Responses. Curr. HIV Res. *11*, 378–387.

Prins, J.M., Jurriaans, S., van Praag, R.M., Blaak, H., van Rij, R., Schellekens, P.T., ten Berge, I.J., Yong, S.L., Fox, C.H., Roos, M.T., et al. (1999). Immunoactivation with anti-CD3 and recombinant human IL-2 in HIV-1-infected patients on potent antiretroviral therapy. AIDS *13*, 2405–2410.

Rasmussen, T.A., and Søgaard, O.S. (2018). Clinical Interventions in HIV Cure Research. Adv. Exp. Med. Biol. *1075*, 285–318.

Rasmussen, T.A., Tolstrup, M., Brinkmann, C.R., Olesen, R., Erikstrup, C., Solomon, A., Winckelmann, A., Palmer, S., Dinarello, C., Buzon, M., et al. (2014). Panobinostat, a histone deacetylase inhibitor, for latent-virus reactivation in HIV-infected patients on suppressive antiretroviral therapy: a phase 1/2, single group, clinical trial. Lancet HIV *1*, e13–e21.

Razooky, B.S., Pai, A., Aull, K., Rouzine, I.M., and Weinberger, L.S. (2015). A hardwired HIV latency program. Cell *160*, 990–1001.

Rhode, P.R., Egan, J.O., Xu, W., Hong, H., Webb, G.M., Chen, X., Liu, B., Zhu, X., Wen, J., You, L., et al. (2016). Comparison of the Superagonist Complex, ALT-803, to IL15 as Cancer Immunotherapeutics in Animal Models. Cancer Immunol. Res. *4*, 49–60.

Riddler, S.A., Zheng, L., Durand, C.M., Ritz, J., Koup, R.A., Ledgerwood, J., Bailer, R.T., Koletar, S.L., Eron, J.J., Keefer, M.C., et al.; AIDS Clinical Trials Group A5342 Protocol Team (2018). Randomized Clinical Trial to Assess the Impact of the Broadly Neutralizing HIV-1 Monoclonal Antibody VRC01 on HIV-1 Persistence in Individuals on Effective ART. Open Forum Infect. Dis. *5*, ofy242.

Robinson, H.L. (2018). HIV/AIDS Vaccines: 2018. Clin. Pharmacol. Ther. *104*, 1062–1073.

Ruelas, D.S., and Greene, W.C. (2013). An integrated overview of HIV-1 latency. Cell *155*, 519–529.

Sampey, G.C., Irlbeck, D.M., Browne, E.P., Kanke, M., McAllister, A.B., Ferris, R.G., Brehm, J.H., Favre, D., Routy, J.-P., Jones, C.D., et al. (2018). The SMAC Mimetic AZD5582 is a Potent HIV Latency Reversing Agent. bioRxiv. https://doi.org/10.1101/312447.

Santra, S., Tomaras, G.D., Warrier, R., Nicely, N.I., Liao, H.-X., Pollara, J., Liu, P., Alam, S.M., Zhang, R., Cocklin, S.L., et al. (2015). Human Non-neutralizing HIV-1 Envelope Monoclonal Antibodies Limit the Number of Founder Viruses during SHIV Mucosal Infection in Rhesus Macaques. PLoS Pathog. *11*, e1005042.

Scheid, J.F., Horwitz, J.A., Bar-On, Y., Kreider, E.F., Lu, C.L., Lorenzi, J.C., Feldmann, A., Braunschweig, M., Nogueira, L., Oliveira, T., et al. (2016). HIV-1 antibody 3BNC117 suppresses viral rebound in humans during treatment interruption. Nature *535*, 556–560.

Siliciano, J.D., Kajdas, J., Finzi, D., Quinn, T.C., Chadwick, K., Margolick, J.B., Kovacs, C., Gange, S.J., and Siliciano, R.F. (2003). Long-term follow-up studies confirm the stability of the latent reservoir for HIV-1 in resting CD4+ T cells. Nat. Med. *9*, 727–728.

Simonetti, F.R., Sobolewski, M.D., Fyne, E., Shao, W., Spindler, J., Hattori, J., Anderson, E.M., Watters, S.A., Hill, S., Wu, X., et al. (2016). Clonally expanded CD4+ T cells can produce infectious HIV-1 in vivo. Proc. Natl. Acad. Sci. USA *113*, 1883–1888.

Sneller, M.C., Justement, J.S., Gittens, K.R., Petrone, M.E., Clarridge, K.E., Proschan, M.A., Kwan, R., Shi, V., Blazkova, J., Refsland, E.W., et al. (2017). A randomized controlled safety/efficacy trial of therapeutic vaccination in HIV-infected individuals who initiated antiretroviral therapy early in infection. Sci. Transl. Med. *9*.

Sneller, M.C., Clarridge, K.E., Seamon, C., Shi, V., Zorawski, M.D., Justement, J.S., Blazkova, J., Huiting, E.D., Proschan, M.A., Mora, J.R., et al. (2019). An open-label phase 1 clinical trial of the anti-$\alpha_4\beta_7$ monoclonal antibody vedolizumab in HIV-infected individuals. Sci. Transl. Med. *11*.

Søgaard, O.S., Graversen, M.E., Leth, S., Olesen, R., Brinkmann, C.R., Nissen, S.K., Kjaer, A.S., Schleimann, M.H., Denton, P.W., Hey-Cunningham, W.J., et al. (2015). The Depsipeptide Romidepsin Reverses HIV-1 Latency In Vivo. PLoS Pathog. *11*, e1005142.

Soriano-Sarabia, N., Bateson, R.E., Dahl, N.P., Crooks, A.M., Kuruc, J.D., Margolis, D.M., and Archin, N.M. (2014). Quantitation of replication-competent HIV-1 in populations of resting CD4+ T cells. J. Virol. *88*, 14070–14077.

Stacey, A.R., Norris, P.J., Qin, L., Haygreen, E.A., Taylor, E., Heitman, J., Lebedeva, M., DeCamp, A., Li, D., Grove, D., et al. (2009). Induction of a striking systemic cytokine cascade prior to peak viremia in acute human immunodeficiency virus type 1 infection, in contrast to more modest and delayed responses in acute hepatitis B and C virus infections. J. Virol. *83*, 3719–3733.

Sun, Z., Denton, P.W., Estes, J.D., Othieno, F.A., Wei, B.L., Wege, A.K., Melkus, M.W., Padgett-Thomas, A., Zupancic, M., Haase, A.T., and Garcia, J.V. (2007). Intrarectal transmission, systemic infection, and CD4+ T cell depletion in humanized mice infected with HIV-1. J. Exp. Med. *204*, 705–714.

Sung, J.A., Lam, S., Garrido, C., Archin, N., Rooney, C.M., Bollard, C.M., and Margolis, D.M. (2015a). Expanded cytotoxic T-cell lymphocytes target the latent HIV reservoir. J. Infect. Dis. *212*, 258–263.

Sung, J.A.M., Pickeral, J., Liu, L., Stanfield-Oakley, S.A., Lam, C.-Y.K., Garrido, C., Pollara, J., Labranche, C., Bonsignori, M., Moody, M.A., et al. (2015b). Dual-Affinity Re-Targeting proteins direct T cell-mediated cytolysis of latently HIV-infected cells. J. Clin. Invest. *125*, 4077–4090.

Sung, J.A., Patel, S., Clohosey, M.L., Roesch, L., Tripic, T., Kuruc, J.D., Archin, N., Hanley, P.J., Cruz, C.R., Goonetilleke, N., et al. (2018). HIV-Specific, Ex Vivo Expanded T Cell Therapy: Feasibility, Safety, and Efficacy in ART-Suppressed HIV-Infected Individuals. Mol. Ther. *26*, 2496–2506.

Tebas, P., Stein, D., Tang, W.W., Frank, I., Wang, S.Q., Lee, G., Spratt, S.K., Surosky, R.T., Giedlin, M.A., Nichol, G., et al. (2014). Gene editing of CCR5 in autologous CD4 T cells of persons infected with HIV. N. Engl. J. Med. *370*, 901–910.

Thaysen-Andersen, M., Chertova, E., Bergamaschi, C., Moh, E.S., Chertov, O., Roser, J., Sowder, R., Bear, J., Lifson, J., Packer, N.H., et al. (2016). Recombinant human heterodimeric IL-15 complex displays extensive and reproducible N- and O-linked glycosylation. Glycoconj. J. *33*, 417–433.

Tobin, N.H., Learn, G.H., Holte, S.E., Wang, Y., Melvin, A.J., McKernan, J.L., Pawluk, D.M., Mohan, K.M., Lewis, P.F., Mullins, J.I., and Frenkel, L.M. (2005). Evidence that low-level viremias during effective highly active antiretroviral therapy result from two processes: expression of archival virus and replication of virus. J. Virol. *79*, 9625–9634.

Tran, T.A., de Goër de Herve, M.G., Hendel-Chavez, H., Dembele, B., Le Névot, E., Abbed, K., Pallier, C., Goujard, C., Gasnault, J., Delfraissy, J.F., et al. (2008). Resting regulatory CD4 T cells: a site of HIV persistence in patients on long-term effective antiretroviral therapy. PLoS ONE *3*, e3305.

Turner, A.W., and Margolis, D.M. (2017). Chromatin Regulation and the Histone Code in HIV Latency. Yale J. Biol. Med. *90*, 229–243.

van Praag, R.M., Prins, J.M., Roos, M.T., Schellekens, P.T., Ten Berge, I.J., Yong, S.L., Schuitemaker, H., Eerenberg, A.J., Jurriaans, S., de Wolf, F., et al. (2001). OKT3 and IL-2 treatment for purging of the latent HIV-1 reservoir

in vivo results in selective long-lasting CD4+ T cell depletion. J. Clin. Immunol. *21*, 218–226.

Varela-Rohena, A., Molloy, P.E., Dunn, S.M., Li, Y., Suhoski, M.M., Carroll, R.G., Milicic, A., Mahon, T., Sutton, D.H., Laugel, B., et al. (2008). Control of HIV-1 immune escape by CD8 T cells expressing enhanced T-cell receptor. Nat. Med. *14*, 1390–1395.

Vibholm, L.K., Konrad, C.V., Schleimann, M.H., Frattari, G., Winckelmann, A., Klastrup, V., Jensen, N.M., Jensen, S.S., Schmidt, M., Wittig, B., et al. (2019). Effects of 24-week Toll-like receptor 9 agonist treatment in HIV type 1+ individuals. AIDS *33*, 1315–1325.

Wagner, T.A., McLaughlin, S., Garg, K., Cheung, C.Y.K., Larsen, B.B., Styrchak, S., Huang, H.C., Edlefsen, P.T., Mullins, J.I., and Frenkel, L.M. (2014). HIV latency. Proliferation of cells with HIV integrated into cancer genes contributes to persistent infection. Science *345*, 570–573.

Wahl, A., Swanson, M.D., Nochi, T., Olesen, R., Denton, P.W., Chateau, M., and Garcia, J.V. (2012). Human breast milk and antiretrovirals dramatically reduce oral HIV-1 transmission in BLT humanized mice. PLoS Pathog. *8*, e1002732.

Wahl, A., Baker, C., Spagnuolo, R.A., Stamper, L.W., Fouda, G.G., Permar, S.R., Hinde, K., Kuhn, L., Bode, L., Aldrovandi, G.M., and Garcia, J.V. (2015). Breast Milk of HIV-Positive Mothers Has Potent and Species-Specific In Vivo HIV-Inhibitory Activity. J. Virol. *89*, 10868–10878.

Wahl, A., De, C., Abad Fernandez, M., Lenarcic, E.M., Xu, Y., Cockrell, A.S., Cleary, R.A., Johnson, C.E., Schramm, N.J., Rank, L.M., et al. (2019). Precision mouse models with expanded tropism for human pathogens. Nat. Biotechnol. *37*, 1163–1173.

Wang, F.X., Xu, Y., Sullivan, J., Souder, E., Argyris, E.G., Acheampong, E.A., Fisher, J., Sierra, M., Thomson, M.M., Najera, R., et al. (2005). IL-7 is a potent and proviral strain-specific inducer of latent HIV-1 cellular reservoirs of infected individuals on virally suppressive HAART. J. Clin. Invest. *115*, 128–137.

Warren, J.A., Clutton, G., and Goonetilleke, N. (2019). Harnessing $CD8^+$ T Cells Under HIV Antiretroviral Therapy. Front. Immunol. *10*, 291.

Watson, D.C., Moysi, E., Valentin, A., Bergamaschi, C., Devasundaram, S., Fortis, S.P., Bear, J., Chertova, E., Bess, J., Jr., Sowder, R., et al. (2018). Treatment with native heterodimeric IL-15 increases cytotoxic lymphocytes and reduces SHIV RNA in lymph nodes. PLoS Pathog. *14*, e1006902.

Webb, G.M., Li, S., Mwakalundwa, G., Folkvord, J.M., Greene, J.M., Reed, J.S., Stanton, J.J., Legasse, A.W., Hobbs, T., Martin, L.D., et al. (2018). The human IL-15 superagonist ALT-803 directs SIV-specific $CD8^+$ T cells into B-cell follicles. Blood Adv. *2*, 76–84.

Whitney, J.B., Lim, S.Y., Osuna, C.E., Kublin, J.L., Chen, E., Yoon, G., Liu, P.T., Abbink, P., Borducci, E.N., Hill, A., et al. (2018). Prevention of SIVmac251 reservoir seeding in rhesus monkeys by early antiretroviral therapy. Nat. Commun. *9*, 5429.

Wightman, F., Solomon, A., Kumar, S.S., Urriola, N., Gallagher, K., Hiener, B., Palmer, S., Mcneil, C., Garsia, R., and Lewin, S.R. (2015). Effect of ipilimumab on the HIV reservoir in an HIV-infected individual with metastatic melanoma. AIDS *29*, 504–506.

Williams, S.A., Chen, L.F., Kwon, H., Fenard, D., Bisgrove, D., Verdin, E., and Greene, W.C. (2004). Prostratin antagonizes HIV latency by activating NF-kappaB. J. Biol. Chem. *279*, 42008–42017.

Winckelmann, A., Barton, K., Hiener, B., Schlub, T.E., Shao, W., Rasmussen, T.A., Østergaard, L., Søgaard, O.S., Tolstrup, M., and Palmer, S. (2017). Romidepsin-induced HIV-1 viremia during effective antiretroviral therapy contains identical viral sequences with few deleterious mutations. AIDS *31*, 771–779.

Wong, J.K., and Yukl, S.A. (2016). Tissue reservoirs of HIV. Curr. Opin. HIV AIDS *11*, 362–370.

Wong, J.K., Hezareh, M., Günthard, H.F., Havlir, D.V., Ignacio, C.C., Spina, C.A., and Richman, D.D. (1997). Recovery of replication-competent HIV despite prolonged suppression of plasma viremia. Science *278*, 1291–1295.

Xu, Y., Trumble, I.M., Warren, J.A., Clutton, G., Abad-Fernandez, M., Kirchnerr, J., Adimora, A.A., Deeks, S.G., Margolis, D.M., Kuruc, J.D., et al. (2019). HIV-Specific T Cell Responses Are Highly Stable on Antiretroviral Therapy. Mol. Ther. Methods Clin. Dev. *15*, 9–17.

Yukl, S.A., Shergill, A.K., Ho, T., Killian, M., Girling, V., Epling, L., Li, P., Wong, L.K., Crouch, P., Deeks, S.G., et al. (2013). The distribution of HIV DNA and RNA in cell subsets differs in gut and blood of HIV-positive patients on ART: implications for viral persistence. J. Infect. Dis. *208*, 1212–1220.

Zerbato, J.M., McMahon, D.K., Sobolewski, M.D., Mellors, J.W., and Sluis-Cremer, N. (2019). Naive CD4+ T Cells Harbor a Large Inducible Reservoir of Latent, Replication-competent Human Immunodeficiency Virus Type 1. Clin. Infect. Dis. *69*, 1919–1925.

Zhen, A., Kamata, M., Rezek, V., Rick, J., Levin, B., Kasparian, S., Chen, I.S., Yang, O.O., Zack, J.A., and Kitchen, S.G. (2015). HIV-specific Immunity Derived From Chimeric Antigen Receptor-engineered Stem Cells. Mol. Ther. *23*, 1358–1367.

Zhen, A., Rezek, V., Youn, C., Lam, B., Chang, N., Rick, J., Carrillo, M., Martin, H., Kasparian, S., Syed, P., et al. (2017). Targeting type I interferon-mediated activation restores immune function in chronic HIV infection. J. Clin. Invest. *127*, 260–268.