Signatures of immune selection in intact and defective proviruses distinguish HIV-1 elite controllers

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Signatures of immune selection in intact and defective proviruses distinguish HIV-1 elite controllers

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Increasing evidence suggests that durable drug-free control of HIV-1 replication is enabled by effective cellular immune responses that may induce an attenuated viral reservoir configuration with a weaker ability to drive viral rebound. Here, we comprehensively tracked effects of antiviral immune responses on intact and defective proviral sequences from elite controllers (ECs), analyzing both classical escape mutations and HIV-1 chromosomal integration sites as biomarkers of antiviral immune selection pressure. We observed that, within ECs, defective proviruses were commonly located in permissive genic euchromatin positions, which represented an apparent contrast to autologous intact proviruses that were frequently located in heterochromatin regions; this suggests differential immune selection pressure on intact versus defective proviruses in ECs. In comparison to individuals receiving antiretroviral therapy, intact and defective proviruses from ECs showed reduced frequencies of escape mutations in cytotoxic T cell epitopes and antibody contact regions, possibly due to the small and poorly inducible reservoir that may be insufficient to drive effective viral escape in ECs. About 15% of ECs harbored *nef* deletions in intact proviruses, consistent with increased viral vulnerability to host immunity in the setting of *nef* dysfunction. Together, these results suggest a distinct signature of immune footprints in proviral sequences from ECs.

INTRODUCTION

Individuals who naturally control HIV-1 viremia in the absence of antiretroviral therapy [ART; here termed as "elite controllers" (ECs)] can be regarded as living evidence that the human immune system is able to effectively restrict HIV-1 replication and fuel hope that a drug-free remission of HIV-1 infection may be inducible in larger numbers of people living with HIV-1 (*1*–*3*). Immunological studies in these individuals have identified several distinguishing host features, most notably with regard to cellular immune responses mediated by HIV-1–specific cytotoxic T cells. In HIV-1 controllers, these cells frequently display a durable memory cell profile, characterized by strong proliferative activities and interleukin-2 (IL-2) secretion (*4*, *5*), and preferentially target epitopes containing topologically important viral amino acid residues (*6*, *7*). Nevertheless, a pool of virally infected cells remains detectable in almost all of these individuals (*8*–*10*). Recent studies have begun to unravel pronounced differences between persisting viral reservoirs in ECs and most ART-treated individuals. Using a near full-length proviral sequencing approach, previous work demonstrated a profound reduction of genome-intact proviruses in ECs (*11*), an observation in line with reduced numbers of replication-competent proviruses determined by quantitative viral outgrowth assays (*12*–*14*). Moreover, these studies also demonstrated that chromosomal integration sites of intact proviruses in ECs were biased toward heterochromatin regions and frequently located to centromeric satellite DNA and to a defined region of genes in chromosome 19 that encode for Zinc Finger Nucleases (ZNF) and are densely packed with repressive chromatin marks (*11*); this represented a marked contrast to proviral integration sites determined in most ART-treated individuals (*15*–*18*). When integrated in these heterochromatin locations, proviral gene expression seems ineffective due to poor access to host transcriptional machinery and the presence of epigenetic chromatin modifications that negatively regulate viral gene transcription. Although positioning in these repressive chromatin locations may not completely prevent proviral gene expression, it is reasonable to assume that intact proviral sequences confined to these heterochromatin positions are more conducive to control by antiviral immune responses and unable to effectively drive viral replication and rebound viremia.

The mechanisms that lead to the distinct intact proviral reservoir profile in ECs are unclear and deserve further clarification. Initial studies concluded that, based on an analysis of proviral integration sites of in vitro–infected cells, heterochromatin regions in the genome of ECs do not display enhanced susceptibility to HIV-1 integration (*11*). Instead, the specific chromosomal integration site landscape of intact proviruses in ECs may represent the result of immune-mediated selection mechanisms. This hypothesis assumes that viral integration into more permissive chromatin regions is associated with a higher risk for exposure to immune recognition, a higher susceptibility to immune-mediated killing, and a higher probability of proviral elimination by antiviral host immune responses, thus implying a selection disadvantage for intact proviral species located in permissive chromatin segments. Together, these considerations suggest intricate and reciprocal

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interactions between the intact proviral reservoir configuration and host immune activity and insinuate that proviral chromosomal positioning may be regarded as an indirect biomarker of host immune selection forces.

Immune selection effects on HIV-1 have traditionally been investigated through an analysis of sequence variations that are consistent with viral mutational escape (*19*). The advent of technologies for analysis of intact and defective proviral sequences in conjunction with the corresponding proviral integration sites (*11*, *18*, *20*, *21*) in the human genome may now allow profiling of footprints of host immune selection effects in greater detail. Here, we used a large set of viral sequencing data to conduct a detailed analysis of immune selection footprints in intact and defective proviral species from ECs and a comparison cohort of ART-treated individuals, paired with an analysis of corresponding proviral chromosomal integration site features. Our results reveal multiple layers of evidence that viral reservoir cells in ECs are subject to host immune selection pressure that can modulate viral reservoir evolution in favor of the host.

RESULTS

Integration site landscapes of intact and defective proviruses in ECs

Our recent work identified a distinct chromosomal integration site profile of intact proviruses in ECs, with a disproportionate overrepresentation in heterochromatin regions (*11*); however, the location of defective proviruses in these individuals has never been systematically analyzed. Defective proviruses frequently account for up to 90% of all detectable HIV-1 proviral DNA in infected individuals and predominantly result from errors during viral reverse transcription (*22*). Here, we extended our prior dataset (comprising proviral sequencing data from $n = 50$ ECs in which at least one intact provirus was detectable) by conducting near full-length individual provirus sequencing (*23*) in eight additional individuals, leading to a total EC study cohort of $n = 58$. In 10 of them, we performed proviral integration site analysis of defective proviruses, resulting in successful integration site mapping for 45 individual proviral species, of which 32 represented independent (nonclonal) proviral sequences. Integration sites of intact proviruses from 14 ECs, partially described in our previous work (*11*), were analyzed for comparison ($n = 103$ individual proviral species and $n = 37$ independent proviral sequences). Integration sites of defective and intact proviruses were analyzed using matched integration site and proviral sequencing (MIP-Seq) (*18*), an experimental approach involving phi29-catalyzed whole-genome amplification (WGA) of single proviruses followed by near full-length proviral sequencing and corresponding chromosomal integration site analysis; this same technique was also applied to the analysis of chromosomal integration sites of intact proviruses from ECs in our previous work (*11*). For comparative purposes, we analyzed near full-length proviral sequencing data in peripheral blood mononuclear cells (PBMCs) of 42 ART-treated individuals and evaluated proviral integration sites of a total of 113 intact ($n = 80$ independent) and 84 defective ($n = 76$ independent) proviruses from 7 ART-treated individuals, generated by MIP-Seq and described in part previously (*18*).

Overall, we analyzed a total of $n = 433$ and $n = 523$ near full-length defective proviruses from ECs and ART-treated individuals, respectively, of which $n = 301$ (in ECs) and $n = 395$ (in ART-treated individuals) corresponded to independent proviral species. Sequence-identical defective proviral species in ECs that were detected at least two times and derived from clonally expanded HIV-1–infected cells accounted for 37.64% of all analyzed defective proviruses (Fig. 1, A to F). This proportion was smaller relative to 65.19% of intact proviruses from ECs that were part of sequence-identical clonal clusters, but not different from the proportions of intact or defective proviral sequences detected within clonal clusters in ART-treated individuals (Fig. 1, F and G). In general, we observed that clonal genome-intact proviruses from both ECs and ART-treated individuals were frequently integrated in members of the ZNF gene family; a notable proportion of clonal defective proviruses from ECs were also integrated in ZNF genes (Fig. 1, C to E and H). In contrast, intact and defective proviruses detected as singlets from either cohort showed no such bias (Fig. 1H and fig. S1A).

Among intact and defective proviruses from ECs and ART-treated individuals integrated in genic regions, we did not detect differences in terms of their orientations relative to host genes or locations in exons/introns (fig. S1, B to E). The fraction of defective proviruses from ECs located in nongenic chromosomal regions reached 3.13%, which was significantly lower ($P = 0.0002$) compared to intact proviruses from ECs but not substantially different from the corresponding proportion of defective proviruses in ART-treated individuals (Fig. 2, A and B; fig. S2A; and data file S1). Moreover, we did not observe a single defective proviral sequence from ECs that was integrated in centromeric DNA or in satellite DNA (Fig. 2B), which generally is infrequently targeted for HIV-1 integration and associated with transcriptional repression of proviral gene expression (*24*, *25*); absence of intact or defective proviruses in such regions was also observed in ART-treated individuals but represented a notable contrast to the strong enrichment of clonal and nonclonal intact proviruses from ECs integrated in centromeric or satellite DNA (Figs. 1H and 2B, fig. S2A, and data file S1). Last, we failed to note a specific enrichment of defective proviruses from ECs in members of the ZNF gene family on chromosome 19, which share a similar chromatin state as satellite DNA and are enriched for repressive chromatin marks (*26*, *27*); the low frequency of defective proviruses from ECs that were integrated in these ZNF genes on chromosome 19 represented a sharp contrast to intact proviruses from ECs but not to intact and defective proviruses from ART-treated individuals (Fig. 1H; Fig. 2, A and C; fig. S2B; and data file S1). When combined, genome-defective proviral sequences located either in nongenic DNA or in ZNF genes represented 15.63% of 32 independent genome-defective proviral sequences and 33.33% of all 45 genome-defective proviral sequences in ECs; these proportions were lower relative to genome-intact proviral sequences in ECs but comparable to the corresponding proportions of proviral sequences in ART-treated individuals (Fig. 2D and fig. S2C).

In a subsequent analysis, we investigated the relative positioning of defective proviruses to host transcriptional start sites (TSS) as determined by RNA sequencing (RNA-Seq) in CD4 T cells (Fig. 2E and fig. S2D). These studies demonstrated that the enhanced distance of intact proviruses from ECs to transcriptionally active genomic regions [described in our previous work (*11*)] was not recapitulated for defective proviruses from ECs. In addition, we evaluated the positioning of proviral integration sites relative to activating and inhibitory histone modifications determined by chromatin immunoprecipitation sequencing (ChIP-Seq) in primary CD4 T cells

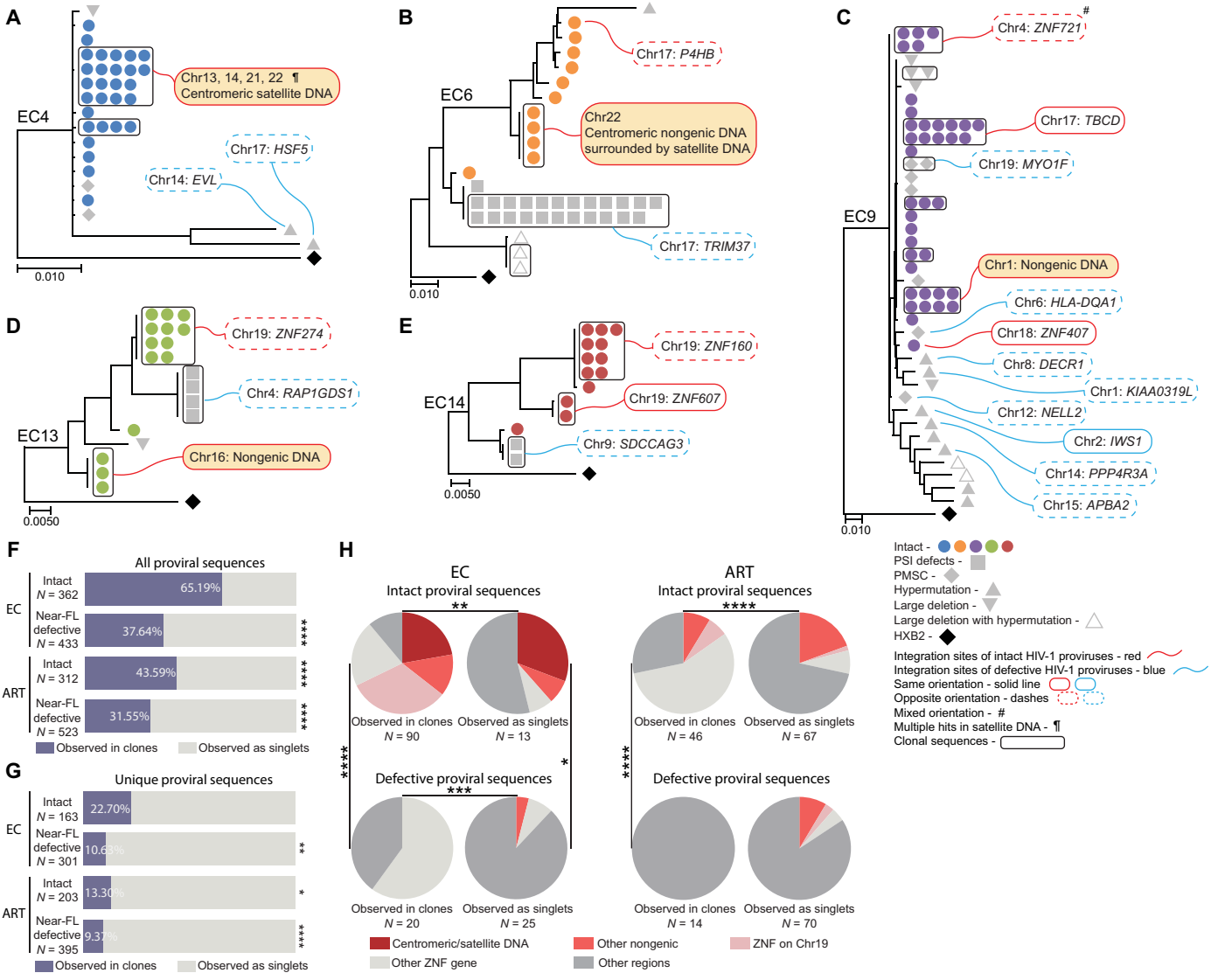

Fig. 1. Chromosomal positioning of defective proviruses from ECs. (**A** to **E**) Maximum likelihood phylogenetic trees of near full-length proviral sequences from five representative elite controllers (ECs) are shown. Symbol shapes indicate proviral sequence classification. Genes harboring proviral integrations were identified using Ensembl (v86); gene names are shown according to the human genome organization (HUGO) classification (www.genenames.org). PSI defects: packaging-signal defects; PMSC: premature stop codons; #, integration sites with mixed orientation among multiple genes; ¶, multihit integration sites that cannot be definitively mapped to one genomic location due to positioning in repetitive centromeric satellite DNA present in multiple regions of the human genome. Clonally expanded proviruses, defined by identical proviral sequences and identical corresponding integration sites, are highlighted in curved black boxes. (**F** and **G**) Proportions of intact and defective proviruses observed in clones (in purple) or as singlets (in gray) from ECs and ART-treated individuals are shown. Clonal sequences are counted individually (F) or only once (G). Statistical comparisons were made relative to intact proviruses from ECs. Near-FL, near full-length. (**H**) Pie charts are shown reflecting proportions of integration sites of intact and defective proviruses in defined genomic regions. Data are shown for clonal sequences (counted individually) and for sequences detected as singlets from ECs and ART-treated individuals. FDR-adjusted two-sided Fisher's exact tests were used in (F) and (G). A chi-square test was used in (H). *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$, and ****$P < 0.0001$.

from the Roadmap Consortium (*26*); these evaluations indicated that, unlike intact proviruses from ECs, defective proviruses from these individuals failed to display an enrichment with the inhibitory histone marks H3K27me3, H3K9me3, and H3K36me3 and a de-enrichment with the stimulatory histone modifications H3K27ac and H3K4me1 in proximity to their chromosomal integration sites (Fig. 2, F and G, and fig. S2E). Chromatin marks for H3K36me3, a marker for constitutive or facultative heterochromatin (*28*), were also elevated at integration sites of intact proviruses from ECs, relative to defective proviruses from ECs and intact or defective proviruses from ART-treated individuals (Fig. 2G). Last, aligning proviral integration sites to three-dimensional chromosomal contact data generated by Hi-C sequencing (*29*) demonstrated that defective proviruses from ECs were predominantly located in compartments A1 and A2 (Fig. 2H and fig. S2F); these compartments mainly include actively expressed chromatin and represent the premier location of intact and defective proviruses from most ART-treated individuals. In contrast, chromosomal locations of intact proviruses from ECs were disproportionately enriched in the heterochromatin compartments B2 and B4. Specifically, integration sites in ZNF

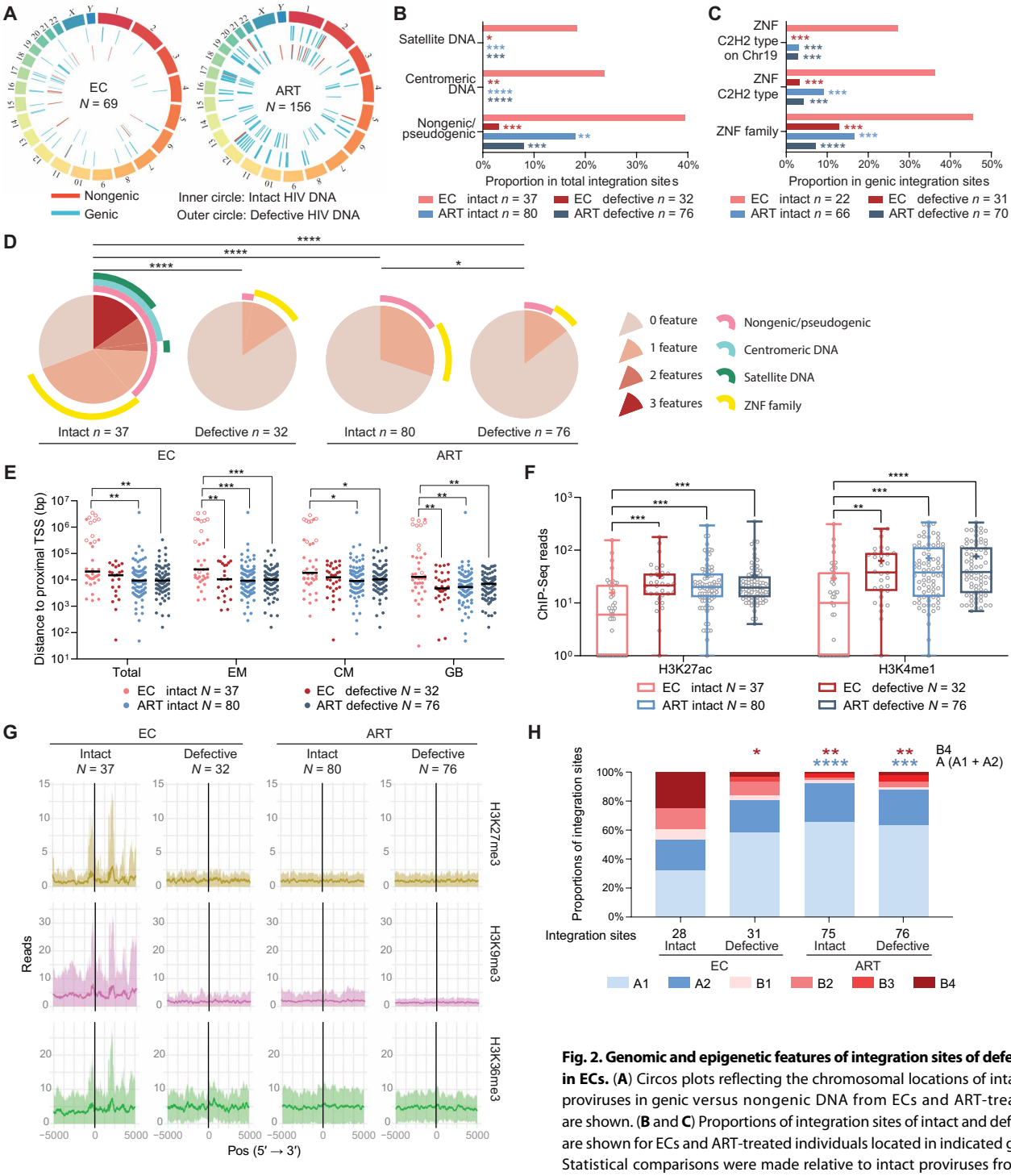

Fig. 2. Genomic and epigenetic features of integration sites of defective proviruses in ECs. (**A**) Circos plots reflecting the chromosomal locations of intact and defective proviruses in genic versus nongenic DNA from ECs and ART-treated individuals are shown. (**B** and **C**) Proportions of integration sites of intact and defective proviruses are shown for ECs and ART-treated individuals located in indicated genomic regions. Statistical comparisons were made relative to intact proviruses from ECs. (**D**) SPICE diagrams demonstrating proportions of intact and defective proviruses with indicated integration site features are shown for ECs and ART-treated individuals. (**E**) Chromosomal distance between integration sites and the most proximal TSS are shown for primary total, effector memory (EM), or central memory (CM) $CD4^+$ T cells or from the Genome Browser database (GB). Horizontal lines reflect the geometric mean. Integration sites in centromeric/satellite DNA are shown in open circles. (**F** and **G**) Numbers of DNA sequencing reads associated with activating (H3K27ac and H3K4me1) (F) or repressive (H3K27me3, H3K9me3, and H3K36me3) (G) histone protein modifications in proximity (±5000 base pairs) to integration sites from intact and defective proviruses are shown for ECs and ART-treated individuals. Median and confidence intervals (1 SD) of ChIP-Seq data from primary memory $CD4^+$ T cells included in the Roadmap repository (*26*) are shown in (G). Box-and-whisker plots reflect mean, median, minimum, maximum, and interquartile ranges. (**H**) Proportions of integration sites located in structural compartments A and B (and associated subcompartments) are shown as determined by Hi-C sequencing data described by Rao *et al.* (*29*). Integration sites in regions not covered in (*29*) were excluded. Clonal sequences are counted once in all panels. FDR-adjusted two-sided Fisher's exact tests were used in (B) to (D) and (H). FDR-adjusted two-sided Kruskal-Wallis nonparametric test were used in (E) and (F). $^*P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$, and $^{****}P < 0.0001$.

genes on chromosome 19 were strongly enriched in compartment B4, consistent with prior results; this chromosomal compartment accounts for a small proportion (0.3%) of the human genome and displays a distinct signature of repressive chromatin marks (*27*, *30*). Because Hi-C next-generation sequencing reads cannot be reliably mapped to centromeric satellite DNA regions, we excluded proviruses located in these regions from this analysis; therefore, the differential representation of intact and defective proviruses from ECs in Hi-C compartments was not driven by proviruses integrated in centromeric regions. Together, these results suggest that, contrary to intact proviruses, defective proviruses from ECs do not show strong integration site biases toward heterochromatin positions; instead, they seem to largely imitate the proviral integration site landscape typically observed in HIV-1–infected individuals undergoing suppressive ART.

Footprints of T cell–mediated immune pressure in intact and defective proviruses from ECs

We next interrogated near full-length proviral sequences from ECs and ART-treated individuals for signs of cytotoxic T lymphocyte (CTL)–driven immune pressure. Aligning HIV-1 amino acid sequences to previously defined, optimal CTL epitopes restricted by autologous human leukocyte antigen (HLA) class I alleles (data file S2), we observed that the proportions of clade B wild-type CTL epitopes in intact proviruses were significantly higher ($P < 0.0001$) in ECs compared to ART-treated individuals (Fig. 3, A and B, and fig. S3, A and B). A similar observation was made for proviruses with 5′ packaging-signal (PSI) defects, with premature stop codons (PMSC) or with hypermutations (Fig. 3A and fig. S3A). Correspondingly, frequencies of proviruses with sequence variations matching recognized escape mutations in CTL epitopes restricted by autologous HLA class I alleles were significantly lower ($P = 0.0021$) in ECs relative to ART-treated individuals (Fig. 3, C and D, and fig. S3, C and D). In both ECs and ART-treated individuals, the lowest frequencies of wild-type CTL epitopes were detected in near full-length hypermutated sequences, likely as a result of apolipoprotein B mRNA-editing enzyme, catalytic polypeptide-like (APOBEC) 3G/3F–induced sequence variations; however, the proportions of wild-type CTL epitopes in hypermutated sequences from ECs were still significantly higher ($P = 0.0010$) compared to ART-treated individuals (Fig. 3A and fig. S3A). In a subsequent, more detailed analysis, we noted that differences in the frequencies of wild-type and escaped CTL epitopes between intact proviruses from ECs and ART-treated individuals were most obvious within the viral gag and pol sequences and less visible within optimal epitopes described in the viral env, nef, and other proteins (Fig. 3, B, D, and E, and fig. S3, B and D). Moreover, we identified a list of immunodominant optimal CTL epitopes within intact proviruses for which the proportions of wild-type sequences in ECs exceeded the corresponding proportions in ART-treated individuals; this list included frequently described CTL epitopes located in gag, pol, and nef, such as A2-SL9 (SLYNTVATL), B8-FL8 (FLKEKGGL), B27-KK10 (KRWIILGLNK), and B57-TW10 (TSTLQEQIGW) (Fig. 3F and fig. S3E).

As an additional analysis step, we evaluated proviral sequence immune adaptation to autologous HLA class I alleles by determining the frequencies of polymorphisms in clade B sequences that were statistically associated with a study participant's expressed HLA class I isotypes, as determined by a previously described algorithm (*31*). The frequencies of sequence variations unrelated to HLA class I isotypes were significantly ($P < 0.0001$) higher in intact proviral sequences from ECs compared to ART-treated individuals; these differences were most visible when selectively analyzing gag, vpr, and env sequences within intact proviruses (Fig. 3, G and H, and fig. S3, F and G) and were also observed in near full-length proviral sequences from ECs that harbored PSI defects, PMSC, or hypermutations (Fig. 3G and fig. S3F). On the other hand, the frequencies of sequence mutations associated with autologous HLA class I alleles were higher in intact and defective near full-length sequences from ART-treated individuals relative to ECs (Fig. 3, I and J, and fig. S3, H and I).

Higher frequencies of wild-type clade B CTL epitope sequences, paired with more limited signs of immune adaption to HLA immune pressure, were most obvious in intact proviruses from ECs integrated in nongenic DNA or in ZNF genes (Fig. 3, K and L, and fig. S3, J and K); although the number of such intact sequences was limited, this observation suggests that proviral species at these chromosomal locations were seeded early in the disease process (before substantial immune adaptation to autologous HLA class I isotypes) and subsequently persisted long term. In contrast, intact proviruses from ECs in other genic positions showed a higher degree of immune adaption (Fig. 3, K and L, and fig. S3, J and K) and most likely represented less ancestral sequences derived from cells infected at more advanced stages of infection. No such differences were observed within intact proviruses from ART-treated individuals. Together, our results show that intact proviral sequences from ECs display more limited signs of CTL-driven mutational escape and sequence adjustment to HLA class I–associated immune pressure relative to ART-treated individuals. This observation is arguably best explained by the smaller number of intact proviruses in ECs and their preferential locations in heterochromatin regions. This specific reservoir configuration may be unable to drive higher plasma viral loads required for effective selection of CTL escape mutations. In the context of ECs, lower numbers of CTL escape mutations may therefore represent an indirect sign of effective viral control.

Sequence variations in contact regions of broadly neutralizing antibodies

We subsequently extended our analysis to investigate signs of humoral immune selection in viral envelope sequences from near full-length proviruses of ECs and ART-treated individuals. We noted that intraindividual *env* sequence diversity, as determined by pairwise comparisons within each study participant in which more than one intact provirus was identified, was more limited in intact proviruses from ECs relative to ART-treated individuals (Fig. 4A). This comparison reached statistical significance for all five variable (V) domains of HIV-1 *env* (V1: $P = 0.0009$; V2: $P = 0.0009$; V3: $P = 0.0001$; V4: $P = 0.0024$; V5: $P = 0.0003$). Moreover, the lengths of the V1V2 domain and the numbers of N-glycosylation sites within *env* sequences from intact proviruses were smaller in ECs (Fig. 4, B and C, and fig. S4, A and B), consistent with more restricted *env* sequence evolution and a lower overall resistance to immune recognition by humoral immune responses (*32*, *33*). The proportion of intact proviruses with R5-tropic envelope sequences in ECs exceeded the corresponding proportion in ART-treated individuals when viral tropism was evaluated using previously developed computational prediction tools (Fig. 4, D and E, and fig. S4C) (*34*).

Taking advantage of an existing compendium of proviral sequence signature mutations that influence susceptibility to broadly

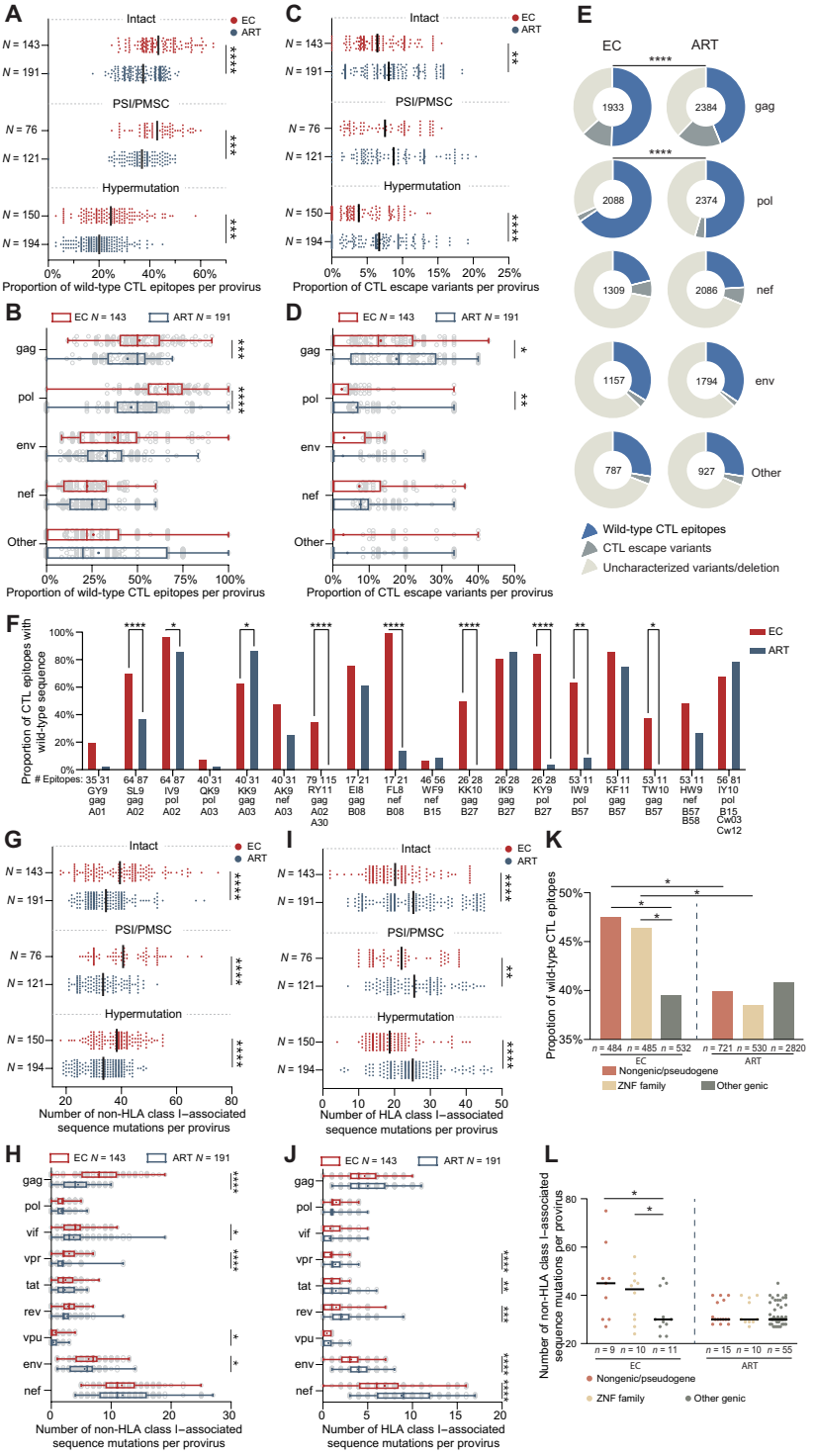

Fig. 3. Footprints of CTL-mediated immune pressure in intact and defective proviruses from ECs and ART-treated individuals. (**A** to **D**) Proportions of optimal CTL epitopes (restricted by autologous HLA class I alleles) with wild-type clade B consensus sequences (A and B) or with previously described CTL escape mutations (C and D) are shown. Each dot represents one provirus. Intact and near full-length proviral sequences with PSI defects/PMSC or hypermutation from ECs and ART-treated individuals are shown in (A) and (C). CTL epitope sequences (restricted by autologous HLA class I alleles) within gag, pol, env, nef, and other HIV-1 proteins from clade B intact proviruses in ECs and ART-treated individuals are shown in (B) and (D). (**E**) Pie charts are shown reflecting the proportions of CTL epitopes displaying the clade B consensus sequences, previously described CTL escape variants, or uncharacterized sequence variations. Data are shown separately for indicated HIV-1 products; the number within each pie chart indicates the total number of analyzed CTL epitopes restricted by autologous HLA class I alleles in each viral protein for each study cohort. (**F**) Proportions of epitopes with wild-type clade B consensus sequences are shown among CTL epitopes restricted by common autologous HLA class I alleles within ECs and ART-treated individuals. (**G** to **J**) Numbers of sequence variations with (I and J) or without (G and H) statistically significant associations with autologous HLA class I alleles are shown, determined as described in (*31*). Each dot represents one provirus. Intact proviruses and near full-length proviral sequences with PSI defects/PMSC or hypermutation from ECs and ART-treated individuals are shown in (G) and (I); sequences of nine individual HIV-1 genes from intact proviruses in ECs and ART-treated individuals are shown in (H) and (J). (**K** and **L**) Proportions of optimal CTL epitopes with wild-type clade B consensus sequences (K) and numbers of mutations nonadapted to autologous HLA class I alleles (L) are shown from HIV proviruses integrated in indicated genomic regions in ECs and ART-treated individuals. Clonal sequences were counted once. Dot plots with median are shown. Box-and-whisker plots reflect mean, median, minimum, maximum, and interquartile ranges. FDR-adjusted two-tailed Mann-Whitney *U* tests were used in (A) to (D) and (G) to (J). Two-sided Fisher's exact tests were used in (E) and (F). FDR-adjusted two-sided Kruskal-Wallis nonparametric test was used in (K) and (L). *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$, and ****$P < 0.0001$.

neutralizing antibodies (bnAbs) (*35*), we evaluated the frequencies of amino acid variations associated with sensitivity or resistance to bnAbs recognizing the CD4 binding site, the V2/V3 envelope regions, or the membrane proximal external region (MPER). Overall, intact proviruses from ECs had significantly ($P < 0.0001$) higher numbers of amino acid positions associated with susceptibility to bnAbs recognizing these env regions, relative to ART-treated individuals; this was also true for near full-length proviruses with PSI defects, PMSC, or hypermutations (Fig. 4F and fig. S4D). Correspondingly, within intact proviruses, the numbers of amino acid changes linked to resistance to bnAbs were significantly ($P < 0.0001$) lower in ECs (Fig. 4G and fig. S4E). Differences in sequence variations consistent with susceptibility to bnAbs between the two cohorts were most pronounced for antibodies targeting the CD4 binding site and for antibodies recognizing the V2 and the V3 envelope regions (Fig. 4, H and I, and fig. S4, F and G).

Hypothesizing that the presence or absence of resistance mutations to bnAbs may possibly be associated with the timing of infection, we stratified all ECs according to the presumed year of HIV-1 acquisition and the duration of recorded HIV-1 infection. We

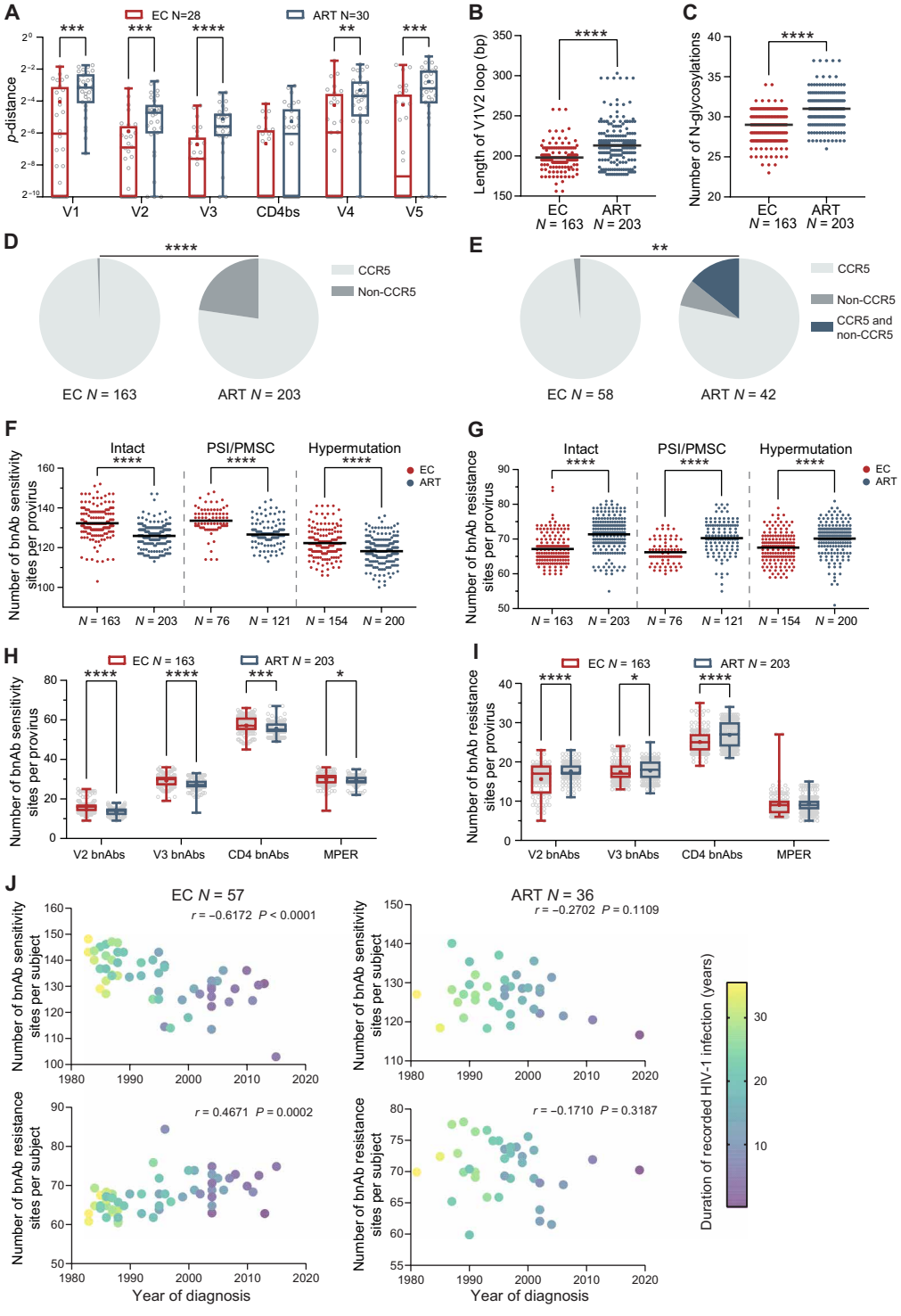

Fig. 4. HIV-1 env sequence diversity in intact and defective proviruses from ECs and ART-treated individuals. (**A**) Mean *p*-distance between indicated *env* sequence domains from intact proviruses is shown, calculated by pairwise comparisons within study participants with at least two detectable intact proviruses. Each symbol represents one individual. (**B**) Lengths of the V1V2 loop in *env* sequences are shown from intact proviruses in ECs and ART-treated individuals. (**C**) Numbers of estimated N-glycosylation sites in *env* sequences are shown from intact proviruses from ECs and ART-treated individuals. (**D**) Pie charts indicating the proportions of intact proviruses with CCR5-tropic or non–CCR5-tropic V3 envelope sequences are shown. (**E**) Pie charts reflecting the proportions of individuals harboring intact proviruses with CCR5-tropic, non–CCR5-tropic, or a combination of both CCR5-tropic and non–CCR5-tropic env sequences are shown. HIV-1 tropism was computationally inferred using Geno2pheno (https://coreceptor.geno2pheno.org/) in (D) and (E). HIV-1 tropism was classified as "CCR5" if the false-positive rate (FPR) predicted by Geno2pheno was >2% and "non-CCR5" if FPR was ≤2%. (**F** to **I**) Numbers of broadly neutralizing antibody (bnAb) sensitivity (F and H) and resistance (G and I) signature sites in indicated proviral sequences are shown. Numbers of signature sites associated with resistance or sensitivity to four classes of bnAbs [specific for V2 domain, V3 domain, CD4 binding site, and membrane proximal external region (MPER)], identified as described before (*35*), were analyzed. (F) and (G) summarize data from intact proviruses and near full-length proviral sequences with PSI defects/PMSC or hypermutation from ECs and ART-treated individuals; (H) and (I) indicate data from intact proviruses from ECs and ART-treated individuals, stratified by bnAb class. (**J**) Correlation analysis is shown between the average numbers of bnAb sensitivity/resistance signature sites within intact proviruses from indicated study individuals and the corresponding HIV-1 infection diagnosis years. Color coding indicates the duration between HIV-1 diagnosis date and sample collection date. Clonal sequences are counted once; the Spearman correlation coefficient is shown for each plot. Dot plots with median are shown. Box-and-whisker plots reflect mean, median, minimum, maximum, and interquartile ranges. FDR-adjusted two-tailed Mann-Whitney *U* tests were used in (A) and (F) to (I). Two-tailed Mann-Whitney *U* tests were used in (B) and (C). Two-sided Fisher's exact test was used in (D) and (E). **P* < 0.05, ***P* < 0.01, ****P* < 0.001, and *****P* < 0.0001.

noted that an earlier time point of infection and a longer duration of HIV-1 infection were associated with a higher number of amino acid positions associated with susceptibility to the four classes of bnAbs within intact proviruses from ECs (Fig. 4J). In contrast, a more recent infection time point and a shorter duration of infection in ECs were associated with a higher number of resistance mutations to bnAbs. This suggests that resistance to bnAbs in ECs may predominantly reflect population-level HIV-1 sequence evolution that is transmitted by founder viruses to ECs at the time of infection. There was no association between timing of HIV-1 infection and

evolution of resistance to bnAbs in ART-treated individuals, likely because antibody resistance mutations in this group of individuals develop as a result of intraindividual antibody-driven immune selection during periods of high plasma viral loads before the institution of ART. Consistent with these results, we noted that intact proviruses from ECs were phylogenetically more closely related to the most recent common ancestor (MRCA) of all intact sequences from ECs and ART-treated individuals combined (Fig. 5, A and B), an observation that was mostly driven by lower frequencies of MRCA sequence divergence within *env* and HIV-1 accessory genes in ECs (Fig. 5C).

Viral *nef* gene deletions in intact proviral DNA

Deletions in viral *nef* sequences have previously been reported in individuals with long-term nonprogressive HIV-1 infection (*36*–*39*), but the frequency of *nef* deletions has never been systematically studied in a large cohort of ECs from which near full-length proviral sequences are available. We observed that *nef* deletions were significantly ($P < 0.0001$) more common among intact proviruses from ECs relative to ART-treated individuals (Fig. 6A and fig. S5A); moreover, the proportion of ECs with shorter *nef* sequences [<600 base pairs (bp), equal to 97% of the length of *nef* in HIV-1 clade B reference sequence HXB2] within intact proviruses reached about 15%, whereas such *nef* deletions were virtually absent in ART-treated individuals (Fig. 6, B and C). Large deletions in accessory genes other than *nef* were very infrequent in all analyzed sequences, independently of the study cohort (fig. S5B). ECs ($n = 9$) with *nef* deletions showed a reservoir profile that differed from the remaining EC cohort ($n = 49$) and instead appeared to resemble ART-treated individuals in several ways: Specifically, the ratio of intact versus defective proviruses in ECs with *nef* deletions was lower (Fig. 6D); moreover, the proportions of epitopes with wild-type sequences or with non-HLA class I–associated sequence mutations in intact proviral sequences were also reduced in this subgroup of ECs (Fig. 6, E and F, and fig. S5, C and D). These findings suggest a replicative history with higher viral turnover in ECs with *nef* deletions. In addition, lower frequencies of polyfunctional HIV-1 gag-specific CD8 T cells secreting both interferon-γ (IFN-γ) and tumor necrosis factor–α (TNF-α) were observed within the EC subgroup with *nef* deletions (fig. S5E). In two ECs (EC20 and EC21), *nef* deletions were detected in all intact proviruses, but not in a subgroup of defective proviruses (fig. S5F), arguing against the acquisition of a *nef*-deleted virus at the time of viral transmission but instead suggesting de novo evolution of *nef*-deleted viral variants within these individuals. Together, our results imply that ECs with *nef* deletions represent a distinct entity of ECs in which viral control is not primarily achieved by antiviral host mechanisms, but instead largely related to infection with or intrahost evolution of an attenuated virus.

APOBEC3G/3F-induced hypermutations

Hypermutated near full-length proviral sequences result from destructive cytosine to uracil changes catalyzed by APOBEC3G/3F during reverse transcription of HIV-1 RNA into DNA (*40*, *41*) and reveal innate immune restriction of HIV-1 replication. We observed that the absolute frequencies of near full-length proviral sequences incorporating hypermutations was smaller in ECs, likely reflecting a generally smaller number of proviral sequences in ECs compared to ART-treated individuals (fig. S6A). The relative proportions of hypermutated sequences among all near full-length proviral sequences tended to be larger in ECs (fig. S6B). Using a recently developed algorithm (*42*), we observed that footprints of APOBEC3G- and APOBEC3F-induced hypermutations were seen at relatively similar proportions in ECs and ART-treated individuals

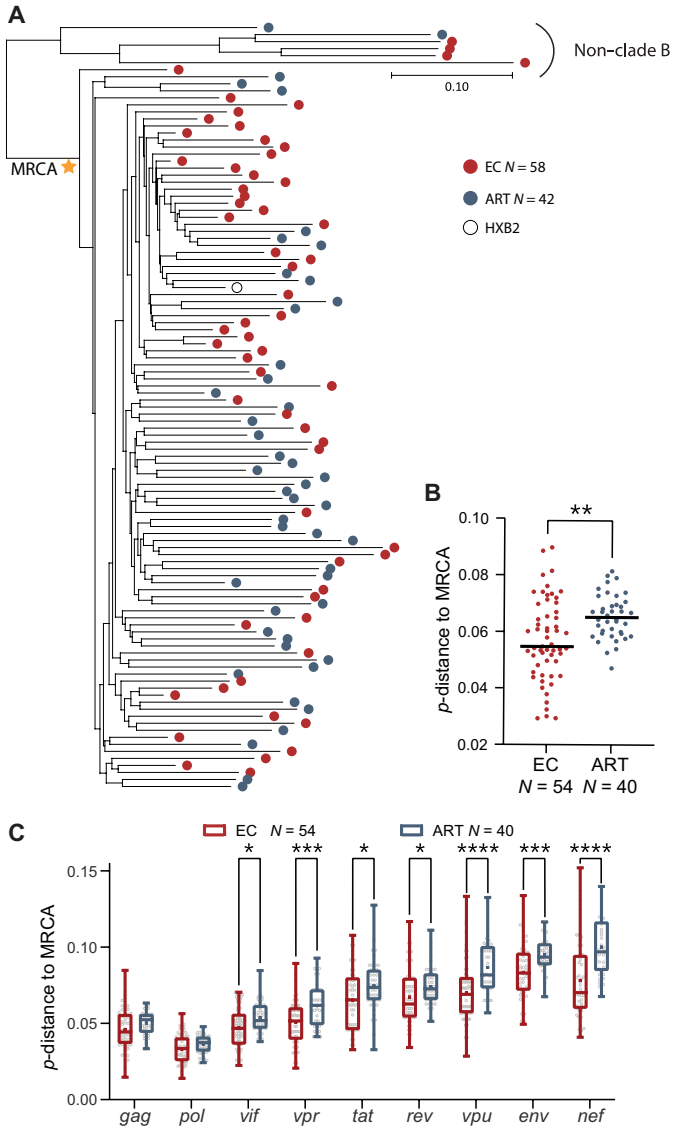

Fig. 5. Phylogenetic associations between intact proviruses from ECs and ART-treated individuals. (**A**) Maximum likelihood phylogenetic trees of intact proviruses from ECs and ART-treated individuals are shown. The most recent common ancestor (MRCA) among clade B intact sequences is marked by a star. HXB2, reference HIV-1 clade B sequence. (**B** and **C**) Genetic distance of all intact clade B sequences to the MRCA is shown. The MRCA and maximum likelihood–corrected distances to the MRCA were estimated in DIVEIN (*72*). (B) Data for all intact proviral sequences. (C) Data for individual HIV-1 genes within intact proviruses. An intraindividual consensus sequence reflecting the dominant base pair residue from all available intact sequences at each base pair position for each study participants was entered into the analysis in (A) to (C); each dot reflects one study participant. Dot plots with median are shown. Box-and-whisker plots reflect mean, median, minimum, maximum, and interquartile ranges. A two-tailed Mann-Whitney *U* test was used in (B). An FDR-adjusted two-tailed Mann-Whitney *U* test was used in (C). $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$, and $^{****}P < 0.0001$.

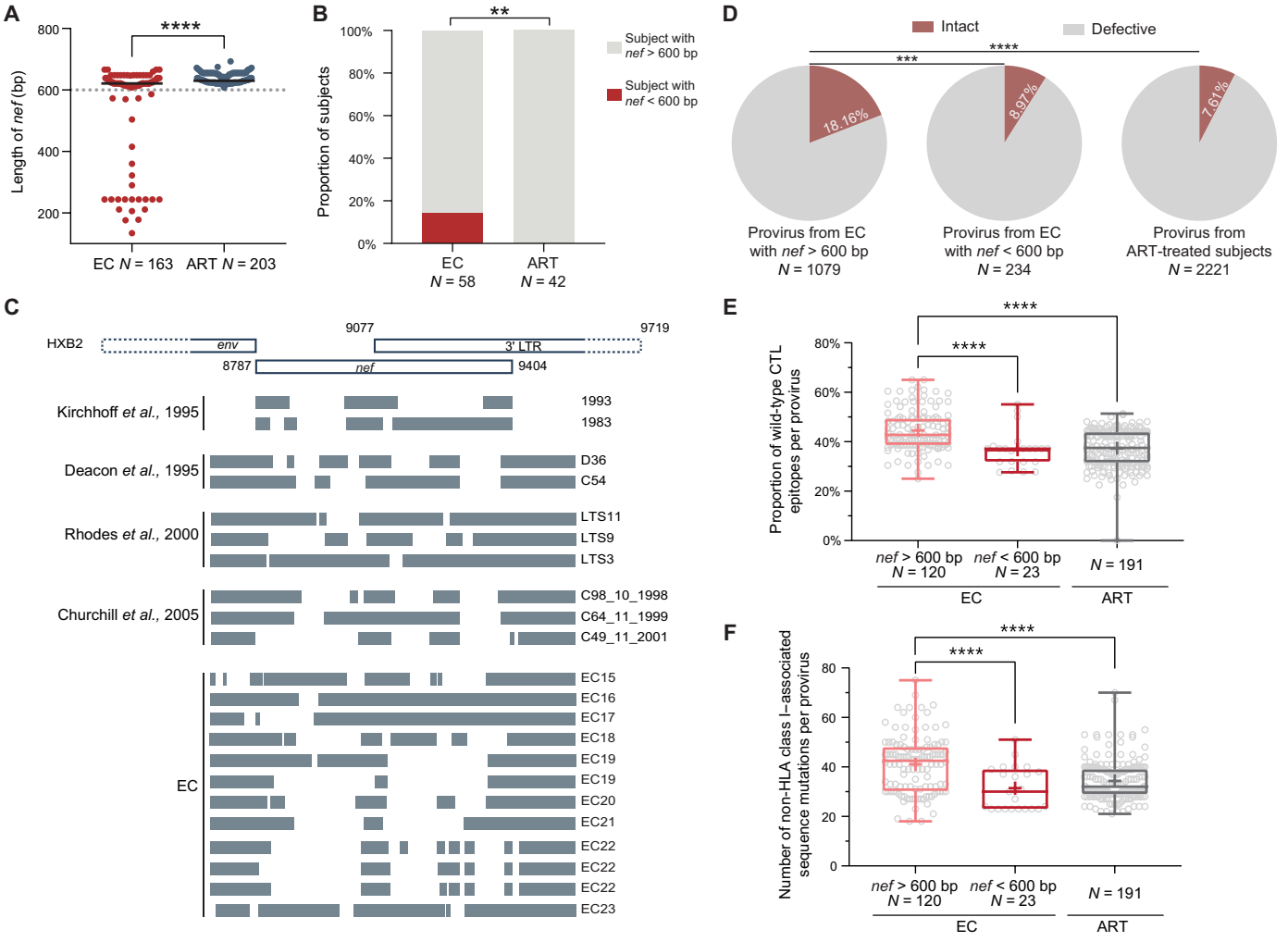

Fig. 6. Intact provirus with large inner *nef* deletions in ECs. (**A**) The length of *nef* genes in intact proviruses from ECs and ART-treated individuals are shown. (**B**) Proportions of individuals with *nef* sequence length of less than 600 bp within all detected intact proviruses are shown. (**C**) A schematic representation shows *nef*/long terminal repeat (LTR) sequence deletions within HIV-1 from previously reported studies (*36*–*39*) and within intact proviruses from ECs. HXB2 was used as the reference; indicated genome coordinates are in HXB2 nomenclature. Indicated *nef* deletions were present in all intact proviruses from each EC, except for EC19 and EC22, in which different types of *nef* deletions were observed in intact proviruses. (**D**) Proportions of intact proviruses are shown out of total proviruses identified from ECs with or without large inner *nef* deletions and from ART-treated individuals. (**E**) Proportions of optimal CTL epitopes with wild-type clade B consensus sequences are shown for intact proviruses with or without large inner *nef* deletions in ECs and ART-treated individuals. (**F**) Numbers of non-HLA class I–associated sequence mutations are shown within intact proviruses with or without large inner *nef* deletions in ECs and ART-treated individuals. Clonal sequences are counted once in all panels. Dot plots with median are shown. Box-and-whisker plots reflect mean, median, minimum, maximum, and interquartile ranges. A two-tailed Mann-Whitney *U* test was used in (A). A two-sided Fisher's exact test was used in (B). An FDR-adjusted two-sided Fisher's exact test was used in (D). FDR-adjusted two-sided Kruskal-Wallis nonparametric tests were used in (E) and (F). $^{**}P < 0.01$, $^{***}P < 0.001$, and $^{****}P < 0.0001$.

(fig. S6, C to F); proviral hotspots that were preferentially hypermutated within specific regions of near full-length proviral sequences were also not notably different between the two cohorts (fig. S6G). Moreover, no consistent difference was found in the proportions of total guanine residues that were hypermutated to adenine in the HIV-1 DNA plus strand when autologous intact HIV-1 proviruses were used as reference (fig. S6H); however, the proportions of GG ➔ GA hypermutations, catalyzed by APOBEC3G, were slightly higher ($P = 0.0062$) in ECs, although there was no difference with regard to GA ➔ AA mutations (catalyzed by APOBEC3F) in this analysis (fig. S6I). The numbers of stop codons introduced by APOBEC3G/3F hypermutations tended to be slightly higher in ECs within the viral *gag*, *rev*, and *vpu* regions (fig. S6J). Overall, these results fail to support a major role of APOBEC3G/3F for contributing to drug-free HIV-1 control in ECs.

DISCUSSION

A broad consensus exists that elite, drug-free control of HIV-1 replication is, in most cases, mediated by host immune factors. However, elite control may not simply occur because of the presence of potent antiviral immune responses to suppress ongoing viral replication; in addition, immune responses in ECs may select for a specific viral reservoir structure that is unable to effectively drive

rebound viremia and more conducive to viral immune control. Immune selection has traditionally been analyzed by investigating viral sequence variations consistent with mutational escape; however, proviral chromosomal integration site profiling might represent a complementary, equally informative approach for unraveling immune selection effects. Here, we performed simultaneous assessments of individual proviral sequences and their corresponding chromosomal locations to generate a comprehensive analysis of the proviral reservoir landscape of intact and defective proviruses from ECs. These investigations demonstrated an atypical reservoir profile of intact proviruses in ECs, characterized by intact proviral species that displayed very limited evidence of CTL- or antibody-driven escape mutations, but were preferentially located in heterochromatin regions that are generally disfavored for proviral integration (*43*–*45*). This specific reservoir profile represented a sharp contrast to autologous defective proviruses and to intact and defective proviruses from ART-treated individuals, which were predominantly integrated in permissive chromatin locations and, in the case of intact proviral sequences from ART-treated individuals, frequently exhibited more evidence of mutational escape from adaptive host immune responses. We propose that this specific profile of intact proviruses in ECs is the result of host immune pressure that effectively eliminates many proviral species before viral escape mutations can be effectively selected for. The net outcome of such immune pressure in ECs appears to be a skeleton reservoir consisting of a limited collection of intact proviral species that remain fully susceptible to host immune recognition but resist immune-mediated elimination through chromosomal integration into heterochromatin locations conferring deep latency and protecting against immune targeting.

The low frequency of HLA class I–associated sequence variations in CTL epitopes from ECs represents an unexpected and perplexing result, specifically because CTL-driven viral mutational escape has been described in circulating HIV-1 RNA sequences from ECs on numerous occasions (*46*–*48*). However, the low frequency of escape mutations in intact proviruses from ECs reported here should not be interpreted as evidence of low immune selection pressure but could instead be viewed as a paradoxical footprint of the extraordinary antiviral immune activity in ECs. Counterintuitively, more limited signs of immune adaptation in viral sequences can be equally associated with very weak or very strong immune selection activity (*49*); in contrast, immune escape typically observed in HIV-1–infected individuals is best explained by an intermediate degree of immune pressure that can select for sequence variations but is unable to control the disease (*49*). Our data are also in line with previous reports suggesting that the degree of viral adaptation to HLA class I–mediated immune pressure is critical for driving HIV-1 disease progression, possibly exceeding the impact of viral fitness (*50*). In ECs, the low numbers of sequences harboring escape mutations may be partially related to the lower viral reservoir population pool size; in addition, we propose that the integration of intact proviruses into less permissive integration sites can restrict the viral replication rate through negative regulation of proviral transcriptional activity. In the setting of such a small, presumably weakly inducible reservoir, viral production and turnover may be insufficient to drive effective viral escape, and, when it occurs, mutated viral species can likely be readily eliminated by HIV-specific CD8 T cells before reseeding of a new viral reservoir. Recognition of mutated viral epitopes by HIV-1–specific CD8 T cells from ECs has been documented before (*6*, *51*, *52*). Higher cell-intrinsic susceptibility of CD4 T cells to CTL killing, previously hypothesized for ECs (*53*), may also be contributing to the fast elimination of newly infected cells, as may other, non–CTL-dependent immune mechanisms (*54*). Together, these data suggest that, in ECs, refueling of viral reservoir cells through ongoing viral replication is ineffective when viral production is low and antiviral immunity is high; instead, the proviral reservoir in ECs seems mostly or almost entirely fueled by clonal proliferation of latently infected cells harboring early-seeded intact proviruses that display only limited signs of immune adaptation. In the future, it may be possible to evaluate specific proviral reservoir features in the slightly larger group of "viremic controllers," which maintain low HIV-1 replication rates (typically less than 2000 copies/ml) in the absence of therapy. In such individuals, phylogenetic signs of ongoing, low viral replication rates might be more obvious (*55*).

An important finding here is that defective proviruses from ECs were frequently integrated in rather typical chromosomal locations in introns of highly expressed genes, in contrast to atypical locations of intact proviruses. Within the 32 defective proviral species we analyzed, not a single integration site in centromeric satellite DNA was noted; moreover, no proviral integrations of defective proviruses into Krüppel-associated box ZNF genes on chromosome 19 were noted, which are densely covered with heterochromatin proteins (*27*). These observations support the hypothesis that the atypical integration site landscape of intact proviruses from ECs is not the result of alternative integration site preferences in ECs. We propose that the differential integration site landscape between intact and defective proviruses from ECs is most likely related to the ability of immune cells to distinguish cells infected with intact versus defective proviruses. Immune cells likely mount different degrees of immune selection pressure against cells harboring intact proviruses that are able to release fully functional infectious virions versus cells encoding for defective proviruses that are only able to produce viral proteins or gene transcripts (*56*, *57*). The exact immune mechanisms that enable such a differential immune recognition will need to be clarified in the future, but evidence suggesting different degrees of immune selection pressure for cells encoding for intact versus defective proviruses has been observed in a number of recent studies: For instance, Peluso *et al.* (*58*), Falcinelli *et al.* (*59*), and Gandhi *et al.* (*60*) observed a faster longitudinal decline of intact versus defective proviruses in ART-treated adults, a finding that was also made in a longitudinal evaluation of HIV-1–infected infants who started ART immediately after birth (*61*). Moreover, Einkauf *et al.* (*18*) noted that, within HIV-1–infected adults undergoing 8 to 10 years of ART, the frequency of intact proviruses in nongenic regions and in opposite orientation to host genes tended to be higher relative to defective proviruses.

An important question that deserves future consideration is the possible role of defective proviruses in ECs for maintaining antiviral immune responses. It is theoretically conceivable that intact proviruses in these individuals, due to their positions in heterochromatin, are only weakly able to secrete sufficient amount of viral antigen to maintain a functional T cell response, the immunological hallmark of antiviral immunity in ECs (*4*, *5*, *62*). Therefore, persistence of a functional T cell response in ECs may largely be driven by viral antigen produced by defective proviruses, which, based on their chromosomal locations, seem better positioned to secrete a tailored dose of viral proteins that is sufficient to drive the maintenance of

HIV-1–specific T cells. Thus, defective proviruses may possibly act as equivalents of a replication-defective vaccine vector that is stably integrated into host DNA and serves as a durable immunogen. However, this view should not downplay the possibility that a residual transcriptional activity may be ongoing in intact proviruses from ECs, despite their integration in heterochromatin positions, and contribute to maintaining antiviral T cell responses.

Our study is limited to an examination of immune selection markers in proviral sequences from one time point in each study participant; longitudinal investigations will be needed to extend this analysis in the future. Moreover, our work involved large and diverse cohorts (58 ECs and 42 ART-treated participants), and we cannot exclude that these differences in the duration of infection may have influenced our study results. Last, our study included only near full-length (greater than 8000 bp) defective HIV-1 proviruses, but it is possible that signs of immune selection may be more pronounced in smaller defective proviral sequences with larger deletions; sequencing of a larger library of defective proviruses will allow for this to be addressed in the future.

Although our results indicate distinct immune selection footprints in ECs, they also show some evidence of immune selection of viral reservoir cells in ART-treated individuals. In particular, we found that integration sites of clonally expanded intact proviruses from ART-treated individuals were frequently located in ZNF family genes, which typically are enriched for the inhibitory histone modification H3K9me3 (*63*, *64*). This chromatin mark facilitates epigenetic transcriptional silencing through the human silencing hub complex, also termed the HUSH complex (*65*). Within ZNF genes, repressive chromatin marks tend to cluster across the gene bodies and the 3′ end of genes (*64*). HIV-1 integration in close proximity to such inhibitory chromatin features may provide a preferred genomic niche for proviruses in proliferating T cells, arguably because cell proliferation does not lead to proviral reactivation when HIV-1 is integrated into the more repressive chromatin environment at ZNF gene loci. Therefore, integration into ZNF genes may offer protection against immune recognition and confer a longitudinal selection advantage. Although we observed a larger proportion of intact proviruses from ECs displaying repressive integration site features compared to ART-treated individuals, our results suggest that immune selection processes in ECs are only gradually but not fundamentally different from ART-treated individuals. Therefore, it remains possible that intensification of antiviral host immune activity through strategies such as therapeutic vaccines may be able to increase immune selection of reservoir cells in ART-treated individuals, possibly to an extent that they may approximate an EC-like "blocked and locked" reservoir profile facilitating the natural control of HIV-1 replication.

MATERIALS AND METHODS

Study design

The objective of this study was to investigate classical escape mutations and HIV-1 chromosomal integration sites of intact and defective HIV-1 proviral sequences from ECs. HIV-1–infected study participants, including 58 ECs and 42 ART-treated participants, were recruited at the Massachusetts General Hospital (MGH), the Brigham and Women's Hospital (BWH) (both in Boston, MA, USA), the San Francisco General Hospital (San Francisco, CA, USA), and the University Hospital of Sevilla (Spain). No formal sample size calculations, randomizations, or investigator blinding operations were performed. Clinical and demographical characteristics of study participants are summarized in table S1. PBMC samples were obtained according to protocols approved by the respective Institutional Review Boards. HLA class I typing was performed using a targeted next-generation sequencing method, as described previously (*66*).

HIV-1 DNA quantification by droplet digital polymerase chain reaction

PBMCs were subjected to genomic DNA extraction using the DNeasy Blood and Tissue Kit (QIAGEN DNeasy, #69504). Total HIV-1 DNA were detected using droplet digital polymerase chain reaction (ddPCR) (Bio-Rad), using primers and probes described previously (*11*). The droplets were subsequently read by the QX200 droplet reader (Bio-Rad), and data were analyzed using QuantaSoft software (Bio-Rad).

Whole-genome amplification

Isolated genomic DNA was diluted to single viral DNA copies according to ddPCR results, so that one HIV-1 provirus was present in about 20 to 30% of wells. Subsequently, DNA in each well was subjected to multiple displacement amplification with phi29 polymerase (QIAGEN REPLI-g Single Cell Kit, #150345) per the manufacturer's protocol. After this unbiased WGA, DNA from each well was split and separately subjected to viral sequencing and integration site analysis, as described below.

HIV near full-length proviral sequencing

Proviral sequences were amplified from genomic DNA or WGA products using a near full-length PCR approach (*23*) or a non-multiplexed five-amplicon approach (*18*) and visualized by agarose gel electrophoresis (Quantify One and ChemiDoc MP Image Lab, Bio-Rad). Near full-length (greater than 8000 bp) and five-amplicon positive products were subjected to Illumina MiSeq sequencing at the MGH DNA Core facility. Resulting short reads were de novo assembled using UltraCycler v1.0 and aligned to HXB2 using multiple sequence comparison by log-expectation (MUSCLE) to identify large deletion, premature/lethal stop codons, out-of-frame indels, internal inversions, or 5′ PSI defects, using an automated in-house pipeline written in Python scripting language (https://github.com/BWH-Lichterfeld-Lab/Intactness-Pipeline). The presence or absence of APOBEC3G/3F-associated hypermutations was determined using the Los Alamos National Laboratory (LANL) HIV Sequence Database Hypermut 2.0 program. Viral sequences that lacked all the defects mentioned above were termed "intact."

Integration site analysis

Integration sites associated with individual viral sequences were obtained by integration site loop amplification, using a protocol previously described (*16*), or by ligation-mediated PCR [Lenti-X Integration Site Analysis Kit (Takara Bio, #631263)] (*17*). DNA produced by WGA was used as template. Resulting PCR products were subjected to next-generation sequencing using Illumina MiSeq. MiSeq paired-end FASTQ files were demultiplexed; small reads (142 bp) were then aligned simultaneously to human reference genome GRCh38 and HIV-1 reference genome HXB2 using bwa-mem (*67*). Biocomputational identification of integration sites was performed according to previously described procedures (*16*, *68*).

Sequence analysis

The near full-length HIV-1 proviral sequences were aligned to the clade B reference sequence HXB2 using multiple alignment using fast Fourier transform (*69*) or Clustal W (www.ebi.ac.uk/Tools/msa/clustalw2). Nucleotides and translated amino acid sequences for each of the nine HIV-1 gene products were obtained using Gene Cutter (www.hiv.lanl.gov/content/sequence/GENE_CUTTER/cutter.html). Clades of intact HIV-1 proviral sequences were determined using the LANL HIV Sequence Database Recombinant Identification Program (www.hiv.lanl.gov/content/sequence/RIP/RIP.html). For each clade B proviral sequence, the optimal CTL epitope sequences restricted by autologous HLA class I alleles within nine HIV-1 genes were identified using the A-List (data file S2) (*70*), which includes the best-defined HIV-1 CTL/CD8$^+$ T cell epitopes from the LANL HIV Immunology Database. The "CTL/CD8$^+$ Epitope Variants and Escape Mutations" table from the same database was used to classify epitope sequences from each provirus as wild-type, escaped, or uncharacterized according to the respective HIV-1 subtype and HLA allele (data file S2). The number of sequence mutations associated with HLA class I-mediated pressure was calculated in clade B proviruses as previously described (*31*). The sensitivity of proviral species to bnAbs were estimated by calculating the number of amino acid signature sites associated with sensitivity to four bnAb classes within the env amino acid sequence from each provirus, as previously described (*35*). The *p*-distance and length of HIV-1 genes were calculated by molecular evolutionary genetics analysis X (www.megasoftware.net). The number of N-glycosylation sites in env was predicted by N-GlycoSite (www.hiv.lanl.gov/content/sequence/GLYCOSITE/glycosite.html) (*71*). HIV-1 tropism was analyzed by Geno2pheno (https://coreceptor.geno2pheno.org/) within the V3 loop sequence from each intact provirus. HIV-1 tropism was classified as "CCR5" if the false-positive rate (FPR) predicted by Geno2pheno was >2%, and "non-CCR5" if FPR was ≤2%. Phylogenetic trees were inferred by the Maximum Likelihood method using PhyML and visualized in FigTree (http://tree.bio.ed.ac.uk/software/figtree). The MRCA and distance to the MRCA were estimated in divergence, diversity, informative sites, and phylogenetic analyses (DIVEIN) (*72*). APOBEC3G- or APOBEC3F-associated hypermutations were calculated as described in (*42*) and in the LANL HIV Sequence Database Hypermut 2.0 program.

Intracellular cytokine staining

PBMCs were stimulated with anti-CD28/CD49d antibody (1 μg/ml; BD FastImmune) and 2 μg/ml of overlapping peptide pools spanning the HIV-1 clade B sequence of gag. After 1 hour of incubation, brefeldin A (1 μg/ml; BioLegend) and GolgiStop (1 μg/ml; BD Biosciences) were added and cultured overnight. Cells stimulated with phytohemagglutinin (2 μg/ml) served as positive control. After stimulation, cells were stained in FACS (fluorescence-activated cell sorting) buffer with surface antibodies against CD3 [2 μl per million cells; APC (allophycocyanin)–Cy7, HIT3a, BioLegend], CD8 [2 μl per million cells; PerCP (peridinin-chlorophyll-protein)–Cy5.5, SK1, BD Biosciences], and LIVE/DEAD Blue Viability Dye (1 μl per million cells; Invitrogen) at 4°C for 15 min. Then, cells were treated with fixation and permeabilization solutions and stained for 30 min at room temperature with antibodies against IFN-γ (3 μl per million cells, phycoerythrin-Dazzle, B27, BioLegend) and TNF-α (3 μl per million cells; Brilliant Violet 711, Mab11, BioLegend). Cells were then acquired on a BD LSRFortessa cytometer (BD Bioscience) at the Ragon Institute Imaging Core Facility at MGH and analyzed using FlowJo software (BD Biosciences).

RNA-Seq, ChIP-Seq, and Hi-C sequencing data

RNA-Seq data generated from primary CD4 T cells and described in a previous publication (*11*) were used for analysis. These data are deposited in the National Center for Biotechnology Information Gene Expression Omnibus (NCBI GEO) (accession number GSE144334). ChIP-Seq data are derived from primary human memory CD4 T cells and are included in the Roadmap Consortium portal (www.roadmapepigenomics.org/). Hi-C sequencing data used in this study were described by Rao *et al.* (*29*).

Statistical analyses

Raw, individual-level data for experiments, where $n < 20$, are shown in data file S3. Data are shown as pie charts, simplified presentation of incredibly complex evaluations (SPICE) diagrams, scatterplot (indicating median), box-and-whisker plots (indicating the median, minimum, maximum, interquartile ranges, and mean as "+"). Differences were tested for statistical significance using Mann-Whitney *U* tests, Fishers' exact tests, chi-square tests, and two-sided Kruskal-Wallis nonparametric tests, as appropriate. $P < 0.05$ was considered significant; false discovery rate (FDR) correction was performed using the Benjamini-Hochberg method (*73*). Analyses were performed using GraphPad Prism, SPICE, and R software.

SUPPLEMENTARY MATERIALS

www.science.org/doi/10.1126/scitranslmed.abl4097
Figs. S1 to S6
Table S1
Data files S1 to S3

View/request a protocol for this paper from *Bio-protocol*.

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Signatures of immune selection in intact and defective proviruses distinguish HIV-1 elite controllers

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Understanding elite controllers

Some individuals living with HIV-1 are able to control viral loads without the need for antiretroviral therapy (ART). However, it is not clear what distinguish these elite controllers (ECs) from individuals who require ART to control viral replication. Here, Lian *et al.* compared chromosomal integration sites and escape mutations between ECs and ART-treated individuals living with HIV-1 to understand the role of immune pressure. The authors observed differences in proviral integration sites between the two groups and showed that proviral sequences from ECs had fewer escape mutations in epitopes recognized by cytotoxic T cells. Together, these findings further explain why some individuals may be able to control HIV-1 viral loads without ART.