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Regulatory T cells generated early in life play a distinct role in maintaining self-tolerance

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Aire is an important regulator of immunological tolerance, operating in a minute subset of thymic stromal cells to induce transcripts encoding peptides that guide T-cell selection. Expression of Aire during a perinatal age-window is necessary and sufficient to prevent the multi-organ autoimmunity characteristic of Aire-deficient mice. We report that Aire promotes the perinatal generation of a distinct compartment of Foxp3$^+$CD4$^+$ regulatory T (Treg) cells, which stably persists in adult mice. This population has a role in maintaining self-tolerance, transcriptome and activation profile distinguishable from those of Tregs produced in adults. Underlying the distinct Treg populations are age-dependent, Aire-independent differences in the processing and presentation of thymic stromal-cell peptides, resulting in different T-cell receptor repertoires. Our findings expand the notion of a developmentally layered immune system.

Individuals with APECED (autoimmune polyendocrinopathy-candidiasis-ectodermal dystrophy) have a mutation in the gene encoding Aire. Such individuals, and mice lacking Aire, develop multi-organ autoimmune disease. Aire promotes immunological tolerance by inducing, specifically in thymic medullary epithelial cells (MECs), a large repertoire of mRNA transcripts encoding proteins characteristic of differentiated cell-types (peripheral-tissue antigens, PTAs), such as insulin or casein-α. Peptides derived from these proteins are displayed on major histocompatibility complex (MHC) molecules at the MEC surface. The MHC:PTA-peptide complexes negatively select thymocytes whose antigen (Ag) receptors (T cell receptors, TCRs) are engaged too aptly. In addition, MECs can positively select Foxp3$^+$CD4$^+$ regulatory T (Treg) cells (*1*, *2*), at least some of them in an Aire-dependent manner (*3*, *4*). Cross-presentation of Aire-induced PTAs by thymic dendritic cells (DCs) also occurs, and can promote either negative or positive selection (*4*, *5*). Aire's presence during the first few weeks of life is necessary and sufficient to guard against the autoimmune disease characteristic of *Aire*-knockout (KO) mice (*6*). We sought to uncover the root of this unexpected finding.

To compare the effectiveness of clonal deletion in perinatal and adult mice, we examined the thymus of young and old *Aire*-WT and *Aire*-KO animals expressing 1) membrane-bound ovalbumin driven by the rat insulin promoter (RIP-mOva), and thereby within MECs; and 2) TCRs that recognize a peptide of ovalbumin presented by MHC-II molecules (OT-II) (*7*, *8*). In both perinatal and adult mice, Aire-dependent clonal deletion was readily evident (fig. S1).

As a first step in comparing the Treg compartments, we enumerated Foxp3$^+$CD4$^+$ T cells in the thymus of progressively older *Aire*-WT and -KO mice (Fig. 1A and fig. S2A). While a few Tregs were detected in the thymus of WT individuals two days after birth, a substantial population was evident only on day 4, and it gradually increased through day 35. KO mice showed a similar pattern of Treg accumulation in the thymus, but their fractional representation was reduced *vis-à-vis* WT littermates through day 35, and their numbers until day 10. Results were similar in the periphery (fig. S2A and B).

To address the relative importance of the Treg compartments for the maintenance of immunological tolerance, we used a NOD.*Foxp3-DTR* system to deplete Tregs during the day 0-10 or day 35-45 age-window, and followed the mice until fifteen weeks of age (or loss of ≥ 20% body weight). Depletion of Tregs during the 0-10 day window resulted in significant weight reduction by 16 days of age (even though Treg numbers were normal by day 11-12), and ≥20% weight loss in all mice by 24 days (Fig. 1B). All individuals showed the multi-organ autoimmunity typical of *Aire*-KO mice on the NOD genetic background (Figs. 1B and fig. S3). In contrast, Treg ablation during the 35-45 day window had no significant effect on either weight gain or survival, although there were some mild manifestations of autoimmunity in scattered individuals (figs. S3 and S4).

We next performed a complementation experiment to rule out the trivial explanation that perinatal mice are non-specifically perturbed by the repeated injection of DT. Addition of Tregs from 20-day-old Treg-replete, but not Treg-depleted, donors to recipients perinatally depleted of Tregs resulted in a striking improvement in the autoimmune manifestations (figs. S5 and S6). To confirm that the critical per-

inatally generated Treg population was, indeed, Aire-dependent, we transferred Tregs isolated from 20-day-old *Aire*-WT or -KO mice into either Treg-depleted (Fig. 1C and D) or *Aire*-KO (fig. S7) perinates. For both types of recipient, only the perinatal Tregs from WT mice protected from development of the characteristic "Aire-less" autoimmune disease. Thus, Aire promotes the generation of Treg cells during the perinatal age-window. Mice lacking these cells phenocopy *Aire*-KO mice; exhibiting a spectrum of pathology that differs substantially from that of mice either constitutively lacking Tregs or depleted of them as adults (*9–11*).

An inducible Treg lineage-tracer system (*12*) allowed us to explore the functional and phenotypic properties of perinatally generated Tregs. In NOD-backcrossed Foxp3$^{eGFP\text{-}Cre\text{-}ERT2}$xR26Y mice, all Foxp3^{+}CD4^{+} cells express GFP; treatment with tamoxifen turns on yellow fluorescent protein (YFP) in the Tregs extant during drug coverage, rendering them GFP/YFP double-positive thereafter. We first used this system to examine the stability of Tregs made perinatally. Lineage-tracer mice were injected with tamoxifen from days 0-10 or 35-45, and their splenic Treg compartment analyzed 1 day, 1 week or 8 weeks later (Fig. 2). The adult-tagged and perinate-tagged Treg populations were both readily discernible the day after termination of tamoxifen, constituting about a quarter of the Foxp3^{+}CD4^{+} compartment. For adult-tagged Tregs, this fraction remained similar throughout the period examined. In contrast, perinate-tagged Tregs dwindled to a minor component of the Foxp3^{+}CD4^{+} compartment between 1 and 8 weeks after cessation of labeling. This reduction in fractional representation was a dilution effect as total Treg numbers increased exponentially during this time. In fact, the actual numbers of perinate-tagged Tregs was very stable over the two months examined.

The persistence of the tagged Treg populations permitted us to address the functionality of perinatally generated Tregs by conducting a four-way comparison (as schematized in fig. S8A). Mice were treated with tamoxifen from 0-10 or 35-45 days, and were then left unmanipulated until 60 days of age, at which time the GFP^{+}YFP^{+} (tagged) Treg and GFP^{+}YFP^{-} (bulk) Treg populations were sorted and transferred into newborn *Aire*-KO mice. According to all criteria evaluated, disease was not affected by introduction of adult-tagged Tregs nor either control bulk Treg population (Fig. 2B-D and fig. S8B). In contrast, addition of perinate-tagged Tregs resulted in substantial reversal of the typical *Aire*-KO pathology (but with substitution of the insulitis characteristic of classical NOD mice) (Fig. 2E and fig. S8B). These findings argue that the Treg population generated perinatally has distinct functional properties that persist within the adult environment.

We also sorted GFP^{+}YFP^{+} and GFP^{+}YFP^{-} CD4^{+} T cells from 8-10 week-old mice whose Tregs had been labeled between 0 and 10 or 35 and 45 days after birth, and analyzed their transcriptomes. Distinct sets of genes were either over- (pink) or under-expressed (green) in Treg cells tagged perinatally *vis-à-vis* the bulk Treg population of the same mice, but were not differentially transcribed in mice whose Tregs were labeled as adults (Fig. 3A, table S1). Overlaying the standard Treg signature on a volcano plot comparing the two labeled Treg populations revealed an over-representation of Treg "up" genes in perinate-tagged Tregs (Fig. 3B). Indeed, these Tregs performed better than the three comparator populations in a typical in vitro suppression assay (Fig. 3C), perhaps reflecting higher transcription of genes such as *Fgl2, Ebi3, Pdcd1, Icos*, etc (table S1A), previously implicated in Treg effector function (*13–16*). The perinate-tagged Treg population was in a more activated state (Fig. 3D), which fit with its higher content of CD44^{hi}CD62L^{lo} cells (Fig. 3E). It was also more proliferative, as indicated by fractions of EdU-incorporating and of Ki67^{+} cells higher than those of the three comparator populations (Fig. 3F). Indeed, the top pathways over-represented in perinate-tagged Tregs according to Gene-Set Enrichment Analysis (GSEA) were related to DNA replication and cell division (eg, Fig. 3G). We confirmed the elevated expression of a number of functionally relevant genes at the protein level (Fig. 3H and fig. S9).

Lastly, we sought a molecular or cellular explanation for the distinct Treg compartments generated in perinatal and adult mice. We first used a mixed fetal-liver:bone-marrow chimera approach to rule out the possibility that T cell precursors derived from fetal liver hematopoietic stem cells, which service the developing immune system for the first few weeks after birth (*17*), are predisposed to yield Tregs with particular properties, measuring both reconstitution efficiencies and gene-expression profiles (fig. S10).

To facilitate comparison of the repertoires of Aire-dependent PTA transcripts in perinatal and adult MECs, we generated Adig reporter mice, which express GFP under the dictates of *Aire* promoter/enhancer elements (*18*), on either an *Aire*-WT or -KO background. GFP^{+}MHC-II^{hi} cells were isolated from thymic stroma of <3-day-old or 5-week-old animals, and gene-expression profiling performed. The fraction of Aire^{+}MHC-II^{hi} MECs and the Aire mean fluorescence intensity (MFI) were indistinguishable in mice of the two ages (fig. S11A and B). The repertories of Aire-dependent MEC transcripts were also extremely similar (fig. S11C).

Going one step further, we asked whether the similar repertoires of PTA transcripts might still yield distinct sets of MHC-presented peptides, owing to different Ag-processing/presentation machinery in mice of the two ages, which need not be Aire-dependent. Transcripts encoding several molecules implicated in generating or regulating the repertoire of peptides bound to MHC-II or -I molecules were differentially expressed in perinatal and adult MECs (Fig. 4A). The data on *H2-O* transcripts drew our attention because DO is known to inhibit the activity of DM, an "editor" needed for dislodging the invariant chain (CD74) derivative, CLIP, and other peptides from the Ag-binding groove of a maturing MHC-II molecule, enabling effective loading of a

diverse repertoire of peptides (*19*, *20*). Transcripts encoding both DO chains were expressed at a significantly lower level in perinatal than in adult MECs, independently of Aire (Fig. 4B); perinatal MECs also had reduced levels of intracellular DO complexes (Fig. 4C). In addition, they displayed higher intracellular levels of DM complexes (Fig. 4E). Co-plotting intracellular levels of the two complexes at the single-cell level revealed a subset of perinatal MECs with reduced DO and enhanced DM expression (Fig. 4F). A lower DO:DM ratio should promote more effective replacement of CLIP by other peptides. Indeed, a higher percentage of perinatal MECs displayed low levels of or no CLIP (37.6 ± 6.4% vs 20.9 ± 2.2%), and the CLIP MFI was lower for perinatal MECs (761.7 ± 78.7% vs 1019.0 ± 54%) (Fig. 4G). Thus, the repertoires of peptides presented by perinatal and adult MECs are different, the latter appearing to be more limited.

Aire-dependent PTAs can be "cross-presented" by myeloid-lineage cells in the vicinity (*4*, *5*), primarily MHC-II^{hi}CD8α^+ DCs (*4*). Interestingly, this cell-type was present at strongly reduced levels in thymi from perinatal mice (Fig. 4H). Since the splenic MHC-II^{hi}CD8α^+ DC subset showed an even more extreme age-dependence, it is unlikely that this difference is Aire dependent.

Such differences in the Ag processing/presentation machinery of MECs from perinatal and adult mice suggested that their Treg TCR repertoires might diverge. We constrained the inventory of TCRs to be examined by using an approach that had proven fruitful in the past (*21*, *22*). BDC2.5 is a $V_\alpha1^+V_\beta4^+$ T helper cell specificity directed at a pancreatic Ag presented by A^{g7} molecules; so generation of Tregs in BDC2.5/NOD mice is dependent on rearrangement of an endogenous *Tcra* gene and thymic selection on the resulting second TCR$\alpha\beta$ complexes. The fixed $V_\beta4^+$ chain constrains the TCR repertoire, and the analysis is further delimited by sorting individual cells expressing $V_\alpha2$. We sequenced 281 $V_\alpha2^+$ TCR CDR3 regions from splenic Tregs of 3 individual BDC2.5/NOD adults and another 232 from the corresponding population of 3 individual perinates. This restricted, but parallel, slice of the TCR repertoire was clearly different in the two age-groups. Perinate Treg TCRs were less clonally expanded (fig. S12A), had shorter CDR3α stretches (fig. S12B) and, as expected (*23*), had fewer *Tcra* N-region additions (fig. S12C). To permit a more statistically robust assessment, we focused on repeat sequences. There were many more repeated sequences in the adult mice, and very low values were obtained for both the Morisita-Horn Index (0.069 on a scale from 0-1) and the Chao abundance-based Jaccard index (0.058 on a scale from 0-1), indicating that the two repertoires were very different (table S2 and Fig. 4I).

Thus, our data highlight Aire's ability to promote the generation of a distinct compartment of Foxp3$^+$CD4$^+$ Tregs as the explanation for its importance during the perinatal age-window. Given the age-dependent differences in antigen processing machinery and presenting cells we documented, juvenile and older mice are likely to have distinct repertoires of both Aire-dependent and Aire-independent Tregs, selected primarily on Ag:MHC complexes encountered on MECs. These findings add to, rather than negate, Aire's role in clonal deletion of self-reactive thymocytes, established in multiple experimental contexts (*4*, *5*, *24*, *25*).

There are striking similarities in the autoimmune diseases provoked by constitutive genetic ablation of *Aire*, thymectomy at 3 days of age, and perinatal depletion of Foxp3-expressing cells – in particular, the pattern of target tissues on different genetic backgrounds ((*26*, *27*) and Fig. 1). Our studies yield a unifying explanation for these phenocopies: the perinatally generated, Aire-dependent Treg compartment is particularly apt at protecting a defined set of tissues from autoimmune attack, and there may be little overlap with the tissues guarded by adult Tregs. This notion is consistent with the observations that mice which underwent a thymectomy 3 days after birth exhibit multi-organ autoimmune disease but do not have a numerically diminished Treg compartment when they get older (*28*, *29*), and that mice constitutively devoid of Tregs or inducibly depleted of them as adults show a very different spectrum of pathologies (*9*–*11*). Such a dichotomy also provides an explanation for the frequently posed question: why is the autoimmune disease characteristic of both APECED patients and *Aire*-KO mice restricted to such a limited set of tissues? An important implication of this dichotomy is that therapies based on transfer of Tregs isolated from adult donors may not be able to impact a particular subset of autoimmune diseases. Thus, our findings extend the notion of a "layered" immune system (*30*).

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SUPPLEMENTARY MATERIALS
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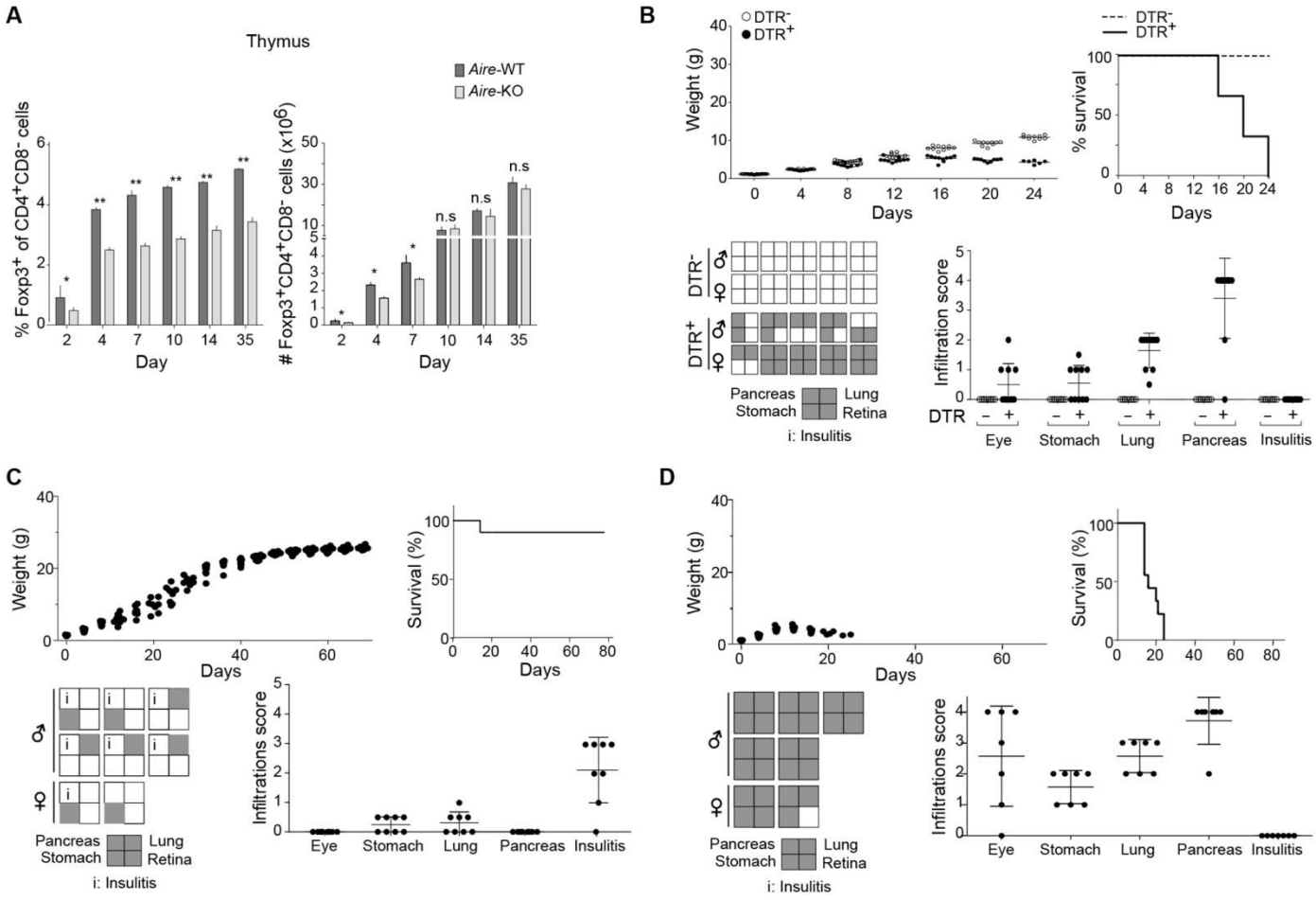

Fig. 1. A perinatal Treg population that is Aire-dependent and guards against the autoimmune manifestations typical of *Aire*-KO mice. (**A**) Summary data for fractional representation (left) and numbers (right) of Foxp3$^+$CD4$^+$CD8$^-$ thymocytes from *Aire*-WT or -KO mice of increasing age. P-values from the Student's *t* test: *, P≤ 0.05; **≤ 0.01; ns = not significant. n=5. Examples of corresponding dot plots can be found in fig. S2A. (**B**) Treg depletion in perinates. Perinatal (0.5 days after birth) NOD.*Foxp3-DTR*$^+$ mice or DTR$^-$ littermates were treated every other day until day 10 with DT, and then followed for manifestations of autoimmune disease. Perinates had to be examined <24 days after birth due to wasting in the DTR$^+$ littermates. Upper left: weight curves. Upper right: survival curves; mice were sacrificed if their weight fell to <20% of that of their DTR$^-$ littermates. Lower left: presence (shaded) or absence of organ infiltrates; "i" indicates that insulitis replaced infiltration of the exocrine pancreas. Lower right: severity of organ infiltration (scored as per the Methods section). n=9. (**C** and **D**) NOD.*Foxp3.DTR*$^+$ mice perinatally depleted of Tregs as per panel B were supplemented on days 12 and 19 with Tregs isolated form 20-day-old *Aire*-WT (C) or -KO (D) littermates. Cohorts were followed until 70 days of age. n = 9. Otherwise set up as per panel B.

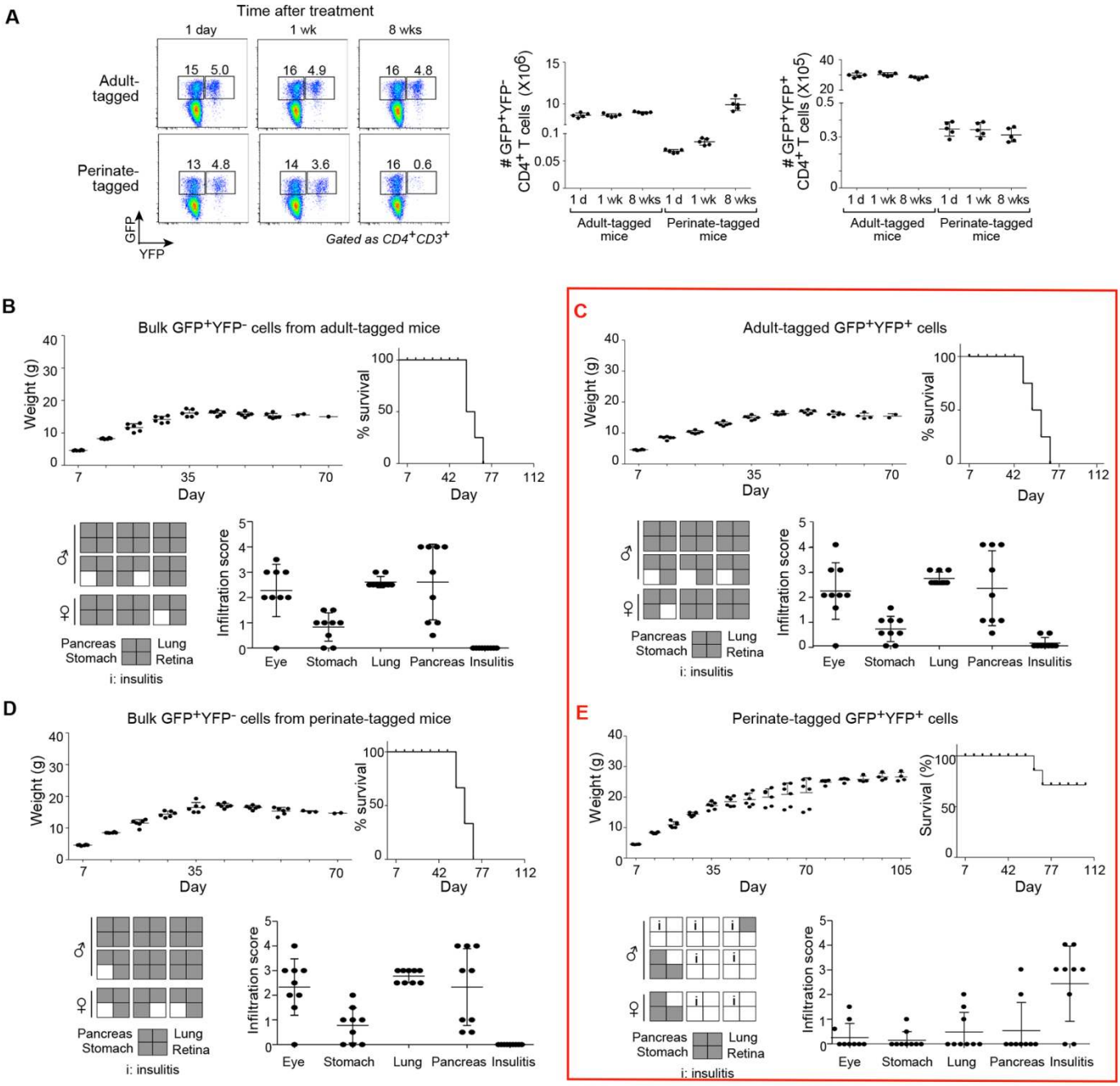

Fig. 2. Stability and function of perinate- versus adult-tagged Tregs. (**A**) Tamoxifen was administered from 0-10 or 35-45 days of age; at various times later, splenocytes were analyzed for GFP and YFP expression by flow cytometry. Left: representative flow-cytometric dot-plots. Numbers represent percentages of $CD4^+3^+$ cells in the designated gates. Center: summary data on numbers of GFP^+YFP^- bulk Tregs. Right: corresponding data on GFP^+YFP^+ perinate-tagged or adult-tagged Tregs from the same mice. n=5. (**B-E**) $1.5x10^5$ Tregs were transferred into *Aire*-KO mice on days 0.5, 3 and 7 after birth, and the recipients were followed until 16 weeks of age. A four-way comparison as schematized in fig. S8A: GFP^+YFP^+ Tregs tagged from 35-45 days of age and isolated from a 60-day-old mouse (C), GFP^+YFP^- bulk Tregs from the same mouse (B), GFP^+YFP^+ Tregs tagged from 0-10 days of age and isolated from a 60-day-old mouse (E), and GFP^+YFP^- bulk Tregs from the same mouse (D). Data organized as per Fig. 1B. The key comparison is boxed..

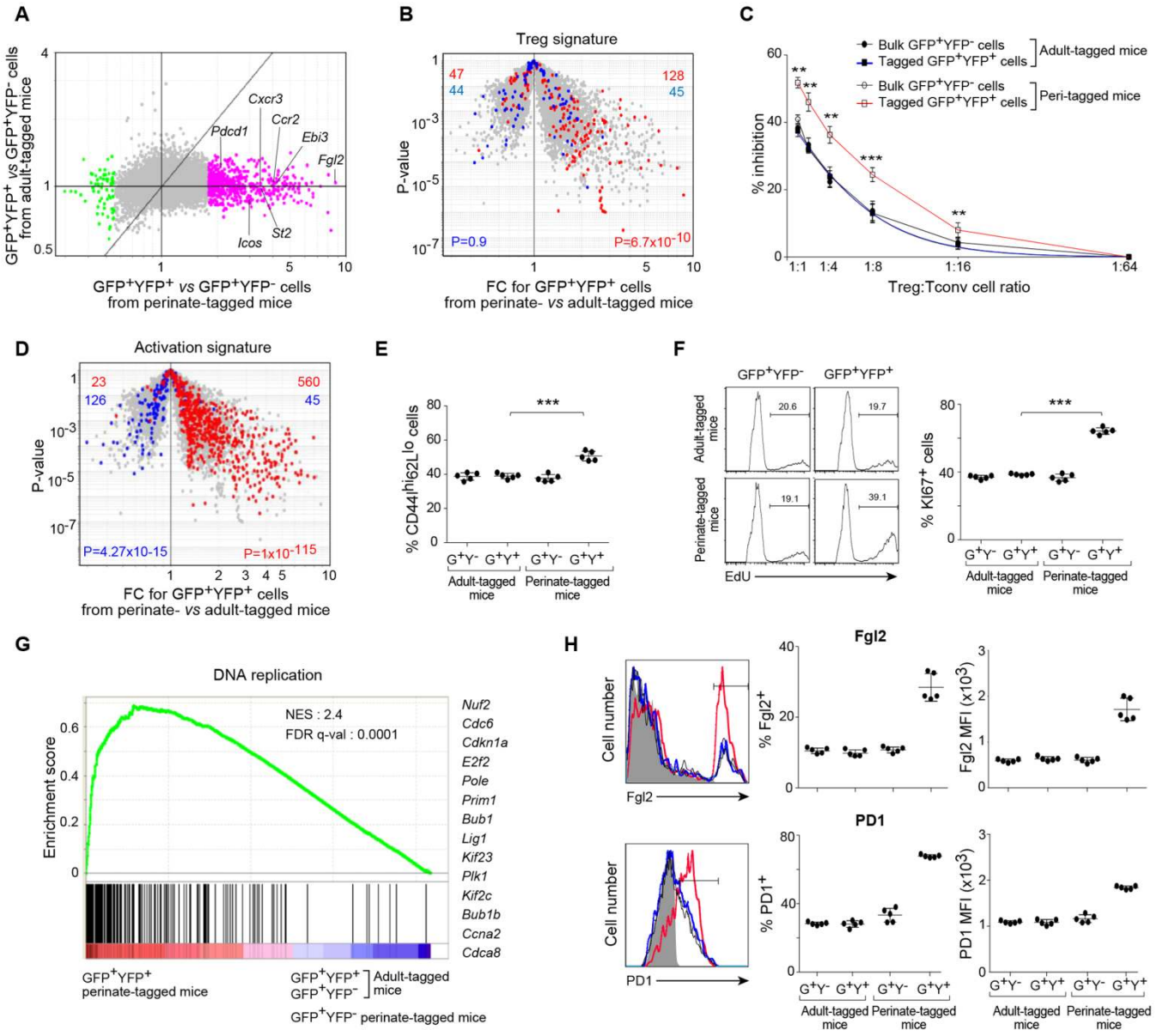

Fig. 3. A distinct transcriptome in perinate-tagged Tregs. The same type of four-way comparison employed in Fig. 2 was conducted except that the sorted cells were analyzed for diverse phenotypic features. (**A**) FC/FC plots comparing perinate-tagged GFP$^+$YFP$^+$ cells vs bulk GFP$^+$YFP$^-$ cells from the same mice (x-axis) and adult-tagged GFP$^+$YFP$^+$ cells vs bulk GFP$^+$YFP$^-$ cells from the same mice (y-axis). Pink dots denote transcripts over-represented in perinate-tagged GFP$^+$YFP$^+$ cells; green dots indicate under-represented transcripts. (**B**) P-value vs FC volcano plot comparing gene expression of perinate-tagged GFP$^+$YFP$^+$ and adult-tagged GFP$^+$YFP$^+$ cells. Red and blue dots indicate up- and down-regulated Treg signature genes, respectively (*31*). P-values from the chi-squared test (**C**) Classical in vitro suppression assay on the four sorted Treg populations. P-values from the Student's *t* test. **, p≤ 0.01; ***, p≤0.001. (**D**) Same volcano plot as in panel B, except up- (red) and down-(blue) regulated activation signature genes (*31*) are superimposed. (**E**) Summary data on late activation marker (CD44^{hi}CD62L^{lo}) expression in the four Treg populations. n=5. P-value from the Students' *t* test ***, P≤0.001. (**F**) EdU uptake (left) and Ki67 expression (right) by the four Treg populations. ***, P≤ 0.001. (**G**) GSEA of transcripts increased in the perinate-tagged GFP$^+$YFP$^+$ *vis-à-vis* the adult-tagged control Treg populations. NES, normalized enrichment score. FDR q-val, false discovery rate. Representative transcripts showing increased expression are shown on the right. (**H**) Flow cytometric confirmation of gene overexpression in perinate-tagged Tregs. For Fgl2 and PD1: Left = representative flow-cytometric histograms; red, perinate-tagged; blue, adult-tagged; black, control bulk populations; gray shading, isotype-control antibody; bar indicates marker positivity. Center = summary data for % of the four Treg populations expressing the marker; Right = summary data for marker MFI in the marker-positive population.

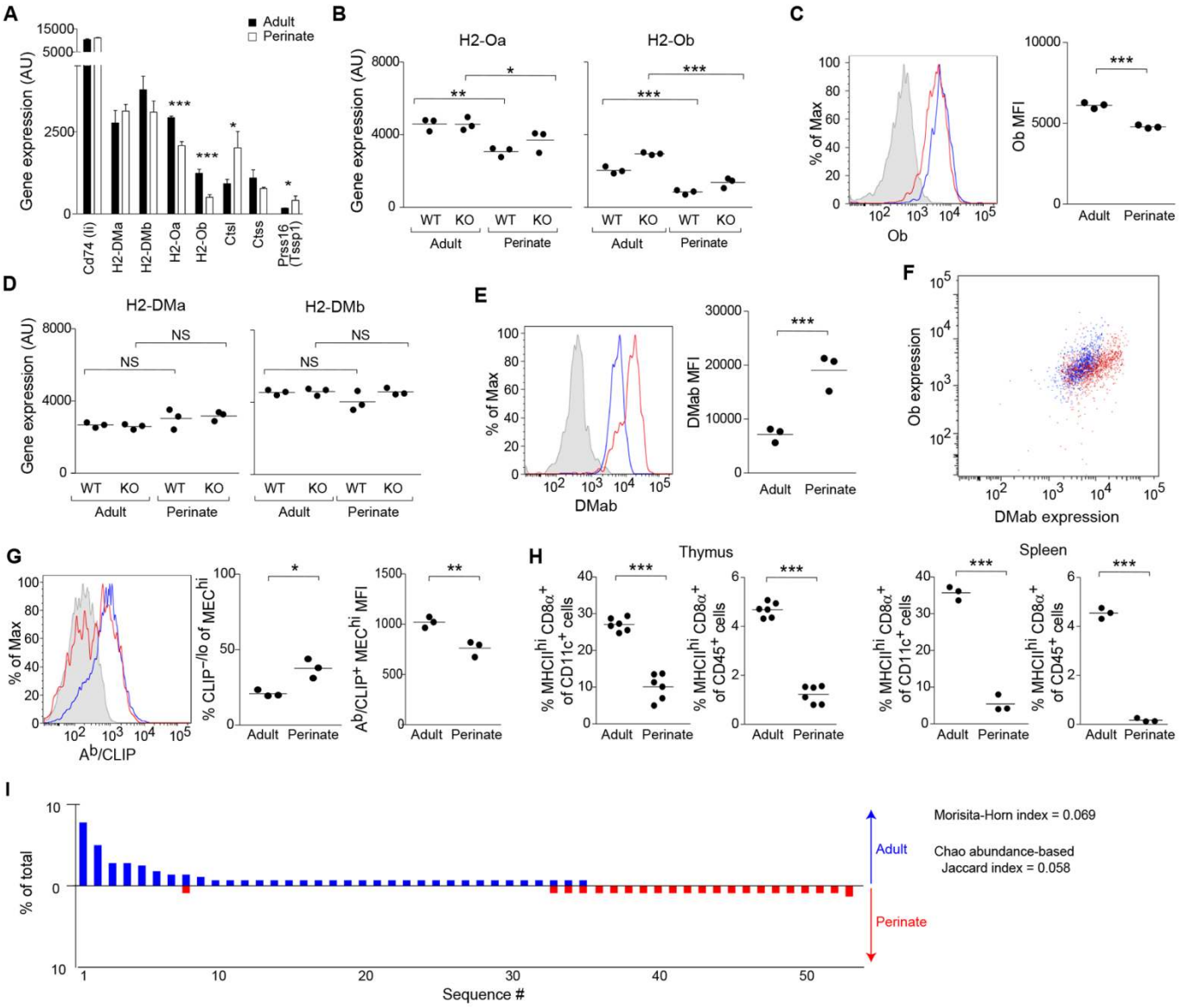

Fig. 4. Age-dependent, Aire-independent differences in the processing and presentation of MEC-generated peptides. (**A**) Microarray-based quantification of transcripts encoding a set of proteins involved in processing/presentation of MHCII-bound peptides. (**B**) Microarray-based quantification of DOa and DOb in MEC^{hi} from *Aire*-WT or -KO adults or perinates. (**C**) Intracellular expression of DOb protein. Left = representative flow-cytometric histograms. Red, perinate; blue, adult; gray shading, negative control staining. Right = summary MFI data. (**D and E**) Same as panels B and C except DMa and DMb were examined. (**F**) Coordinate intracellular staining of DOb and DMab. (**G**) Surface expression of Ab:CLIP complexes on MEC^{hi}. Left = representative flow-cytometric histograms. Red, perinate; blue, adult; gray shading, negative control staining. Center = summary data for % MEC^{hi} expressing little or no CLIP. Right = summary data for MFI. (**H**) Flow cytometric quantification of MHC^{hi}CD8α^+ DCs in perinatal vs adult thymus (left) and spleen (right). Summary data for representation in the CD11c$^+$ (left) and CD45$^+$ (right) compartments. (**I**) High-frequency Vα2$^+$ TCRs from 5wk-old (upper) and 4d-old (lower) BDC2.5/NOD females. These sequences correspond to those in table S2. Bars represent frequency of each sequence. Except for panel I, P-values are from the Student's *t* test: *, P < 0.05; **, P < 0.01; ***, P < 0.001. n=3-6.