Epigenetic mechanisms of regulation of Foxp3 expression

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Regulatory T cells play important roles in the control of autoimmunity and maintenance of transplantation tolerance. Foxp3, a member of the forkhead/winged-helix family of transcription factors, acts as the master regulator for regulatory T-cell (Treg) development and function. Mutation of the Foxp3 gene causes the scurvy phenotype in mouse and IPEX syndrome (immune dysfunction, polyendocrinopathy, enteropathy, X-linked syndrome) in humans. Epigenetics is defined by regulation of gene expression without altering nucleotide sequence in the genome. Several epigenetic markers, such as histone acetylation and methylation, and cytosine residue methylation in CpG dinucleotides, have been reported at the Foxp3 locus. In particular, CpG dinucleotides at the Foxp3 locus are methylated in naive CD4+CD25− T cells, activated CD4+ T cells, and TGF-β−induced adaptive Tregs, whereas they are completely demethylated in natural Tregs. The DNA methyltransferases DNMT1 and DNMT3b are associated with the Foxp3 locus in CD4+ T cells. Methylation of CpG residues represses Foxp3 expression, whereas complete demethylation is required for stable Foxp3 expression. In this review, we discuss how different cis-regulatory elements at the Foxp3 locus are subjected to epigenetic modification in different subsets of CD4+ T cells and regulate Foxp3 expression, and how these mechanisms can be exploited to generate efficiently large numbers of suppressive Tregs for therapeutic purposes.

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promoter regions are also linked with overexpression of CD70, CD3ζ chain, CD40L, CTLA4, ITGAL, interleukin-2 (IL-2), IL-4, IL-10, and interferon-γ (IFN-γ) in CD4+ T cells.17-23 Conditional DNMT1−/− mice, where DNA methylation is ablated from the CD4+CD8− thymocyte stage onwards, show increased production of IFN-γ, IL-2, IL-3, and IL-4 in peripheral T cells after activation compared with littermate-matched controls.24 MBD2−/− mice, which lack another regulatory protein important for maintaining methylation and transcriptional repression, show ectopic expression of IL-4, which is sensitive to DNA methylation under Th1-polarized conditions.25,26 In contrast to naive T cells, effector T cells and Tregs express receptors for inflammatory chemokines and ligands for E- and P-selectin, which help in their recruitment into inflamed tissues.27-29 Treatment of naive CD4+ T cells with 5-aza-2′-deoxycytidine (Aza), which inhibits DNMTs, leads to expression of P-selectin ligand, suggesting that ligand expression is also controlled by DNA methylation.30

Structure of the Foxp3 gene

In Tregs, the Foxp3 gene acts as the master regulator for the development of Tregs, and its constitutive expression is required for Treg-suppressive function.1 Genetic defects in Foxp3 cause the scurfy phenotype in mice and IPEX syndrome (immune dysfunction, polyendocrinopathy, enteropathy, X-linked syndrome) in humans.1,31 The Foxp3 gene possesses 11 coding and 3 noncoding exons.32 The 2 extreme 5′-noncoding exons (−2a and −2b) are separated by 640 bp, and these 2 exons are spliced to a second common noncoding exon (−1). The −2b and −1 exons are separated by approximately 5000 bp and possess several regulatory cis-elements (Figure 1C). It has been noted that a 2-bp (amino acid [AA]) insertion in exon 8 leads to scurfy in mice.32 Sequencing of a large cohort of IPEX persons shows that 60% of patients have missense mutations mainly in exons 9, 10, and 11 (which together form a forkhead domain), and other mutations are distributed throughout the gene.1

Foxp3 protein is highly conserved in bovine, canine, feline, murine, macaque, and humans.33 Indeed, the Foxp3 protein sequences of humans (gene number NP_054728) and mouse (gene number NP_473380) have 86% identity and 91% similarity in their amino acids. Western blot analysis shows that human cells express 2 Foxp3 isoforms. The upper band is similar to the mouse Foxp3, whereas the lower band is unique to humans and lacks exon 2 (amino acids 71-105), which is part of the repressor domain in the Foxp3 protein. This region interacts and represses the function of retinoic acid–related orphan receptor-γ (ROR-γ)34 and ROR-γt.35 Expression of Foxp3 Δexon2 in human CD4+CD25−Foxp3− T cells leads to more IL-2 secretion and proliferation in response to T-cell receptor (TCR) stimulation compared with full-length Foxp3.
Regulation of Foxp3 expression by trans-acting transcription factors

Immediately upstream to the Foxp3 transcriptional start site (−511 to +176) is a region that possesses several important transcription factor-binding sites (AP-1, NFAT) with features indicative of eukaryotic promoters, including TATA, GC, and CAAT boxes. This region acts as a promoter for Foxp3 transcription and is referred to as the proximal promoter region. Other regulatory cis-elements are present between noncoding exons (−2b and −1) or far upstream of the transcriptional start site (−5 kb), and these elements are referred to as the intronic enhancers or upstream enhancers, respectively (Figure 1C). Different extracellular stimuli and intracellular signaling molecules control the development and function of Tregs by regulating the transcription of Foxp3. For example, IL-2 signaling has an important role in the development and function of Tregs, and IL-2 receptor signaling is generally dependent on STAT5. Burchill et al identified 11 STAT consensus sites in Foxp3 (3 at the proximal promoter, 8 between intronic regions), yet only the proximal promoter conserved region shows binding with STAT5 and is dependent on IL-2Rβ signaling. Recently, it has been shown that phosphorylation of STAT1 in Th1 cells by IL-27 and IFN-γ leads to Foxp3 expression, and this is the result of the direct interaction of phosphorylated STAT1 with the Foxp3 proximal promoter in human CD4+ T cells. Conversely, IL-27 also inhibits Foxp3 expression in murine CD4+ T cells in a STAT3-dependent manner, and IL-27 induced murine CD4+ T cells to express IL-10 but not Foxp3. These studies suggest that IL-27 is dispensable for Treg generation and that STAT5 but not other STATs are required for Foxp3 expression.

Small guanosine triphosphate-binding protein superfamily molecules, such as N-Ras or K-Ras, are involved in the control of cell differentiation, proliferation, and apoptosis. Mor et al showed that inhibition of N- or K-Ras signaling in CD4+ T cells leads to induction of NFAT and Foxp3 expression and enhanced Treg-suppressive function. However, the mechanism of Ras signaling to regulate Foxp3 expression is not clearly defined.

In Th1, the IFN-γ–induced protein interferon regulatory factor 1 binds to the Foxp3 proximal promoter and inhibits Foxp3 expression. In Th2, IL-4 inhibits Foxp3 expression in peripheral naive CD4+CD25− T cells by stimulating phosphorylation of STAT6, which binds between exons −2b and −1 (+2459 to +2866 bp) and inhibits TGF-β–induced Foxp3 expression. TGF-β and IL-4 signaling together induce IL-9 secretion, leading to the newly identified IL-9+IL-10+Foxp3+ (Th9) subset.

The vitamin A metabolite retinoic acid (RA) inhibits Th17 cells and induces de novo generation of Foxp3+ Tregs. RA induction of Tregs from naive CD4 T cells may be the result of enhanced TGF-β–driven phosphorylation of SMAD3 along with the inhibition of IL-6 and IL-23 receptor expression. However, RA also enhances TGF-β–induced conversion of naive CD4+ T cells to Tregs, by inhibiting the CD4+CD44+ memory T cells that produce Foxp3 inhibitory cytokines IL-4, IL-21, and IFN-γ. Kang et al showed that all-trans-retinoic-acid induces histone H4 acetylation at the Foxp3 locus and Foxp3 expression in naive CD4+CD25− T cells. RA induces expression of CCR9 and CD103 (αε subunit of α4β7 integrin) on Tregs, and these Tregs showed increased migration to gut-homing chemokine CCL25. Benson at al reported that, in the presence of TGF-β, CD80/86 knockout dendritic cells (DCs) induce increased Foxp3 expression compared with wild-type DCs. The reduced Foxp3 expression with wild-type DCs can be overcome with the addition of RA to culture. Furthermore, Coombes et al showed that mucosal CD103+ DCs are responsible for TGF-β and RA-induced Foxp3 expression. CD103+ DCs express high levels of retinal dehydrogenase (aldh1a2) compared with CD103− DCs, which is required for the conversion of retinal to RA. RA induces Foxp3 expression at the Foxp3 locus and Foxp3 expression in naive CD4+CD25− T cells. RA together with cytokines and T-cell activation signals provided by different subsets of DCs regulate Foxp3 expression in CD4 T cells.

Phosphatidylinositol 3-kinase (PI3K) is induced by TCR and CD28 signaling and is required for cell-cycle progression, cell survival, and proliferation. PI3K signaling activates the Akt-mTOR pathway, Akt signaling interferes with Foxp3 expression, and Foxp3+ Tregs show reduced Akt phosphorylation. CD28 signals can interfere with adaptive Treg differentiation by TGF-β, whereas TCR plus CD28 signals increase Foxp3 enhancer activity and Foxp3 expression. Rapamycin, a chemotherapeutic drug, targets Akt-mTOR signaling and rapamycin-induced differentiation of Tregs and has been used to induce tolerance. Negative regulator molecules, such as SHIP, a lipid phosphatase, hydrolyze phosphatidylinositol 3,4,5-triphosphate, a second messenger of PI3K, and is required for migration of immune cells. FTY720, an agonist, acts as an immunosuppressant by sequestering T cells in lymphoid organs. We showed that receptor S1P1 causes tissue retention by inhibiting the entry of peripheral T cells to afferent lymphatics.

Recently, Liu et al showed that the S1P1 receptor activates Akt-mTOR kinase signaling, thereby inhibiting the development and suppressive function of Foxp3+ Tregs. Sphingosine 1-phosphate (SIP1) is a natural lysophospholipid, which signals through 5 known G protein–coupled receptors (S1P1–S5) and is required for migration of immune cells. FTY720, an agonist, acts as an immunosuppressant by sequestering T cells in lymphoid organs. We showed that receptor S1P1 causes tissue retention by inhibiting the entry of peripheral T cells to afferent lymphatics.

Together, these findings demonstrate that there are several diverse intrinsic and extrinsic signals that regulate of Foxp3 expression and Treg function, yet detailed molecular mechanisms require further investigation.

Role of CpG DNA methylation in Treg development and function

Epigenetic regulation by CpG methylation at specific sites in T cells controls the differentiation of T helper cells. Different regulatory cis-elements are present in the Foxp3 locus. There are regulatory elements present upstream of the transcriptional start...
site (−600 to −1 bp) at the proximal promoter (Figure 1C). Apart from trans-acting factors binding to the proximal promoter, the methylation status of the CpG residues in the proximal promoter region has an essential role in Foxp3 expression. Zorn et al reported that demethylation induced by Aza in human NK cells leads to Foxp3 expression. Subsequently, Kim and Leonard reported that 10% to 45% of the CpG sites in the Foxp3 proximal promoter (−250 to +1) are methylated in naive CD4+CD25− T cells, whereas all were demethylated in nTregs, and TGF-β induces demethylation of CpG at this site in CD4+CD25− T cells. Janson et al showed that this region is approximately 70% methylated in CD4+CD25lo T cells compared with approximately 5% in CD4+CD25hi T cells in humans. These studies demonstrate that demethylation of the proximal promoter is an important regulator of Foxp3 expression.

There are also regulatory cis-elements present in between noncoding exons (−2b and −1) that act as enhancers and are defined as intrinsic enhancers (Figure 1C). This intrinsic region of Foxp3 is highly conserved and is responsible for the regulation of Foxp3 expression. It has been shown that CpG residues in this intrinsic region (+4201 to +4500) are completely methylated in naive CD4+CD25− T cells and fully demethylated in nTregs in mice and in human. Independent studies showed that this region has different levels of demethylation after TGF-β stimulation in mouse and human. The first intrinsic CpG containing region (+4393 to +4506 bp, conserved noncoding sequence 3) has decreased methylation of CpG residues after TGF-β signaling, and after TCR signaling has increased binding to the cyclic-AMP response element–binding protein/activating transcription factor, leading to increased Foxp3 expression. Another evolutionary conserved intrinsic region between exons −2b and −1 (+2177 to +2198, conserved noncoding sequence 2) binds SMAD3 and NFAT and possesses enhancer activity (Figure 1C). Because the SMAD3 and NFAT binding sites (CNS2) and the CpG methylation site (conserved noncoding sequence 3) are present in between the same noncoding exons and do not overlap with each other, this suggests that these cis-elements may be responsible for the regulation of Foxp3 as a result of different extracellular signaling environments. The interaction of these 2 elements, the signals that regulate them, and the interaction of these signals are areas that require further investigation.

We have shown that there is a CpG island approximately 5 kb upstream of the transcriptional start site, and we refer it as the upstream enhancer. The upstream enhancer (−5786 to −5558 bp) is methylated in naive CD4+CD25− T cells, activated CD4+ T cells, and TGF-β–induced Foxp3+ Tregs, but is demethylated in nTregs (Figure 1C). This region functions as an enhancer. In nTregs, but not TGF-β–induced Tregs, this CpG island has acetylated histone 3 indicative of a transcriptionally active site and interacts with the transcription factors Sp1 and TGF-β–induced early 1 product (TIEG1). Conversely, this region is bound by the repressors DNMT1, DNMT3b, MeCP2, and MB2 in naive CD4+CD25− T cells, activated CD4+ T cells, and TGF-β–induced CD4+Foxp3+ T cells. Culture of CD4+CD25− T cells with Aza demethylates the upstream enhancer, leading to positive interactions with transcription factors and markedly increased Foxp3 mRNA and protein expression, and acquired suppressor activity.

TGF-β induces Foxp3 expression in peripheral naive CD4+CD25− T cells; however, its activities are very complex in this regard. In addition to TGF-β receptor–induced SMAD3 signaling for Treg generation, TGF-β–induced signaling may also act via TIEG1 and E3 ubiquitin ligase itch in a ubiquitin-dependent pathway. Venuprasad et al showed that itch−/− and TIEG1−/− naive CD4+ T cells have less Foxp3 induction after TGF-β stimulation, and these Tregs do not protect from antigen-induced airway inflammation. TGF-β also inhibits the phosphorylation of ERK leading to inhibition of DNMT expression; and inhibition of DNMT with siRNA or DNMT inhibitors leads to Foxp3 expression in CD4+ T cells, suggesting that inhibition of DNMT activity plays an important role in Foxp3 expression. These CpG methylation epigenetic markers have been used to screen suppressive Tregs derived from the tissues of cancerous or noncancerous patients.

The inflammatory cytokine IL-6 suppresses the development and function of Tregs. IL-6 induces DNMT1 expression and enhances its activity. IL-6 induces STAT3–dependent methylation of the upstream Foxp3 enhancer by DNMT1 in nTregs, leading to repression of Foxp3. Preactivated CD4+CD25− T cells or CD4+CD25−CD44hi memory T cells express very little Foxp3 after TGF-β stimulation. This is probably the result of high levels of DNMT1 activity in these cells because inhibition of DNMT with Aza or deficiency of DNMT1 in T cells leads to Foxp3 expression, suggesting that regulation of Foxp3 is tightly controlled by epigenetic modification in activated CD4+ T cells.

Together, these reports demonstrate that Foxp3 is regulated by complex mechanisms where many extracellular signals control transacting factors as well as chromatin remodeling through covalent modification of CpG DNA. Thus, TGF-β along with inflammatory cytokines has a different effect than TGF-β alone on the development of Tregs. Understanding these signals and their cumulative intracellular effect on Foxp3 cis-elements at different T-cell developmental stages will be key for manipulating T-cell responses therapeutically (Figure 2).

Role of HDACs in Treg development and function

Acetylated histone is a marker for open chromatin structure. Acetylation of core histone molecules is catalyzed by histone acetyltransferase, and acetyl groups are removed by HDACs. Histone acetyltransferase acetylates the conserved ε-amino group of the lysine residue at the amino-terminus of the histone tail. This decreases the overall positive charge, thereby decreasing histone affinity for negatively charged DNA, and providing a platform for the binding of transcription factors to the chromatin template. According to size, subcellular expression, number of enzymatic domains, and structure, HDACs are divided into 4 classes. Class I HDACs (HDACs 1, 2, 3, and 8) are detected in the nucleus and ubiquitously expressed in different tissues and cell lines. Class II HDACs (HDACs 4, 5, 6, 7, 9, and 10) shuttle between the nucleus and cytoplasm and are expressed in a tissue-specific manner. For example, human HDAC4 is more abundant in skeletal muscle, brain, heart, and ovary, but not detectable in liver, lung, spleen, and placenta. HDAC5 is expressed in mouse skeletal muscle, liver, and brain, but not in spleen. Class III HDACs are composed of NAD+–dependent deacetylases SIRT1 to SIRT7. Class III HDACs are structurally unrelated to class I and class II HDACs. They have a unique enzymatic mechanism of action that requires the cofactor NAD+ for their activity. HDAC11 is the only member of class IV, and its classification is still under debate. Phylogenetic analysis shows that HDAC11 is closely related to HDAC 3 and HDAC8, suggesting that it might be closer to class I than class II. After TCR stimulation, murine CD4+CD25−
naive T cells and CD4+CD25+ nTregs do not show significant differences in the level of class I HDACs, whereas class II HDACs are mainly expressed in Tregs. \(^8^4\) Little else is known about the function and distribution of class II HDACs in nTregs, suggesting an area for productive research.

The N-terminal region of the Foxp3 protein is proline rich, which makes Foxp3 different from the other family members Foxp1, Foxp2, and Foxp4, and this region of Foxp3 recruits the corepressor lysine acetyltransferase TIP60. TIP60 acetylates the Foxp3 protein, and in turn acetylated Foxp3 protein binds to its target gene promoter, such as IL-2, to repress its transcription. The N-terminal region of Foxp3 can also recruit the class II deacetylase HDAC7. \(^8^5\) During T-cell activation, HDAC7 is recruited to the Foxp3 corepressor complex, deacetylates the Foxp3 protein, and thus inhibits Foxp3 function. It is important to note that HDAC7 can also deacetylate histones in the Foxp3 promoter and repress transcription. HDAC inhibitors enhance Foxp3 expression in CD4+CD25+ and CD4+CD25+ T cells, suggesting that HDACs directly regulate both the Foxp3 gene and protein and enhance the suppressive function of Tregs. \(^8^4,8^6,8^7\) Another class II deacetylase, HDAC9, interacts with Foxp3 and down-regulates its acetylation. Treatment with the HDAC inhibitor trichostatin A enhances Foxp3 acetylation and Treg function. \(^8^5\)

TGF-β induces chromatin binding and promoter occupancy of acetylated Foxp3 on the IL-2 promoter. Recently, it has been shown that TGF-β and IL-6 down-regulate the chromatin binding of acetylated Foxp3 to the human IL-2 promoter, and treatment with HDAC inhibitors under these conditions restores the binding of Foxp3 to the IL-2 promoter, suggesting that under inflammatory conditions HDACs play a role in the regulation of Foxp3 function. \(^7^4\)

**Stability of Treg**

The stability of CD4+Foxp3+ T cells is an interesting area in Treg biology that has been recently reviewed. \(^8^9,9^0\) nTregs possess demethylated CpG at the Foxp3 locus and show stable Foxp3 expression, whereas TGF-β induced Tregs show methylated CpG and do not maintain constitutive Foxp3 expression after restimulation in the absence of TGF-β. \(^5^4\) It has been reported that a fraction of Foxp3+CD4+ nTregs adoptively transferred into lymphopenic

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**Role of histone methylation in Treg development and function**

Apart from inheritance of methylated CpG residues in genomic DNA, parental histone molecules can also divide and be transmit-
mice converted into Foxp3- T cells. Under inflammatory conditions, Foxp3+ Tregs lose Foxp3 expression and suppressive function in an IL-6–dependent manner. Yang et al reported that IL-6 and TCR signaling induced down-regulation of Foxp3 expression and led to development of Th17 cells. Using Foxp3-GFP-Cre X ROSA26-YFP dual-reporter mice, Zhou et al showed that approximately 10% of YFP+ T cells lose their Foxp3 expression over time. Recently, we showed that IL-6 induces remethylation of CpG DNA at the upstream enhancer and down-regulates Foxp3 expression in nTregs. It has been reported that Foxp3+ CD4+ Tregs are a very heterogeneous population in mice and humans and different subsets of Tregs possess different levels of CpG DNA methylation at the Foxp3 locus. It has been shown that increased methylation of CpG nucleotides at the Foxp3 locus was linked with less Foxp3 expression, decreased Treg stability, and reduced suppressive Treg function. Epigenetic inheritance during the cell cycle is crucial in maintaining chromatin structure in cell lineages. The extrinsic and intrinsic signals that regulate CpG DNA methylation and perpetuate H3 methylation level at the Foxp3 locus from one cell cycle to another are not understood and require further investigation. These studies will help us to understand the maintenance of Foxp3 stability in Tregs.

Pharmacologic agents that alter epigenetically regulated genes

Epigenetic therapy is an emerging field in pharmacology that promises therapeutic agents for the control of various diseases. Epigenetic drugs can be divided into 2 groups: DNMT or HDAC inhibitors. Some of these inhibitors are shown in Table 1. The prototypic inhibitors 5-azacytidine and Aza were developed as cytotoxic agents and subsequently have been discovered to possess potent DNMT inhibitor activity. These drugs are converted into nucleotide triphosphates and are incorporated in place of cytosine into replicating DNA. Therefore, they are more active in the S-phase of cells. 5-Azacytidine is incorporated into both RNA and DNA, whereas Aza is incorporated only into DNA and is less toxic compared with 5-azacytidine. The disadvantages of azanucleosides are instability in aqueous solutions and strong toxicity. These disadvantages might be overcome by the use of other analogs, such as zebularine, procainamide, 5-fluoro-2'-deoxyctydine, and hydralazine. Procainamide, used to treat cardiac arrhythmias, is a specific inhibitor of DNMT1. Several natural products derived from tea and sponges, such as epigallocatechin-3-gallate, also show DNMT inhibitory activity. Antisense oligonucleotides complementary to the human DNMT1 mRNA are in clinical trials.

There are several HDACs inhibitors available, and some are used clinically for the treatment of neurologic disorders and cancer (Table 1). Importantly, the hydroxamate compounds, trichostatin A and suberoylanilide hydroxamic acid, have been shown to induce Tregs and prolong allograft function in mice. Other HDAC inhibitors are not as potent as hydroxamates for enhancing the suppressive function of Tregs. Epigenetic regulators as immunotherapy

There are a variety of methods by which Tregs can be generated, although many are laborious, inefficient, and expensive. The stability of Foxp3 expression in Tregs is very important for their therapeutic use. The conversion of antigen-specific Tregs into effector T cells will have detrimental effects and limit clinical applicability. Epigenetic regulation may be an efficient therapeutic strategy for generation of stable Tregs and suppression. In vivo injection of HDAC inhibitors increases Treg numbers and function in mice and rhesus. DNMT inhibitors induce strong Foxp3 expression, but associated cell toxicity as well as induction of Th1 and Th2 cytokines limit its use. To overcome these problems, we cultured naive CD4+ T cells with low doses of DNMT inhibitors under TGF-β–induced Treg conditions. After 24 hours, DNMT inhibitor was removed and the T cells further cultured under TGF-β–induced Treg conditions. After this brief exposure, the Foxp3 enhancer was demethylated and stable Foxp3+ Tregs were generated, without indiscriminately activating other gene loci. These Tregs were more stable than conventional TGF-β–induced Tregs and were able to protect from autoimmune colitis and prolong allogeneic islet survival. It has been reported that prolonged in vitro culture of human Tregs leads to methylation of Foxp3 locus and decreased expression of Foxp3 and TGF-β–induced human Tregs are not stable and do not have efficient suppressive function. Using the epigenetic approach, we also generated enhanced Foxp3-suppressive human Tregs that could be used as cell therapy. Human Foxp3+ CD4+ T cells are very heterogeneous and, based on CD25, CD62L, CD45RA, HLA-DR, and ICOS expression, can be divided in different subsets. Miyara et al reported 3 different populations of Foxp3+ CD4+ T cells in the

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<td>5-Aza-2'-deoxycytidine (Decitabine)4,39,29</td>
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<td>Zebularine102</td>
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<td>5-fluoro-2'-deoxycytidine (FCDR)103</td>
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<td>Non-nucleoside analog inhibitors</td>
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<td>Procaine104</td>
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<td>Epigallocatechin-3-gallate (EGCG)105</td>
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<td>N-Phthalyl-L-tryptophan (RG108)9</td>
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<td>Antisense oligonucleotides</td>
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<td>Cyclic tetrapeptides</td>
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<td>Electrophilic ketones</td>
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<td>Trifluoromethyl ketone116</td>
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<td>Miscellaneous compounds</td>
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Peripheral blood mononuclear cells of a healthy man. CD45RA+Foxp3+ resting Tregs and CD45RA-Foxp3+ activated Tregs show completely demethylated CpG at the proximal promoter (−256 to −16 bp) and more than 85% demethylation of the intronic region promoter (+3824 to +3937 bp), and are suppressive. However, CD45RA-Foxp3+ Tregs show decreased demethylation at the proximal promoter and less than 50% demethylation at the intronic region, secrete cytokines such as IL-2 and IFN-γ, and do not show suppressive function. These findings suggest that epigenetic mechanisms provide better strategies to differentiate suppressive Tregs, understand the etiology of immunologic diseases resulting from reduced Treg-suppressive function, and help in designing better approaches to generate suppressive human Tregs.

Perspective on epigenetics in Treg biology

In humans, 1% to 3% of total T cells are CD4+CD25+Foxp3+ Tregs. Tregs have been used experimentally for the tolerance induction and the control of autoimmunity. Remaining to be elucidated is the induction and the control of autoimmunity. These studies suggest that Treg adoptive therapy may provide an effective approach to control alloreactivity. Remaining to be elucidated is the regulation of Foxp3 under inflammatory conditions, such as bone marrow transplantation, where the conditioning regimen leads to enhanced inflammatory responses, or in solid organ transplantation, where inflammation is enhanced by ischemia and reperfusion injury. Recent advances in Treg biology, such as the role of S1P1 in T-cell migration as well as its interference in the suppressive function of Tregs, provide avenues for the development of therapeutic agents. Further studies about Akt-mTOR signaling on epigenetic modification at the Foxp3 locus may provide a better understanding for the use of chemotherapeutic agents, such as FTY720 and rapamycin in the generation of stable Foxp3+ Tregs. Similarly, the use of immunotherapeutic drugs that inhibit the down-regulation of Foxp3 under inflammatory condition may be potent strategies to enhance the function of Tregs. DNMT and HDAC inhibitors may be candidates as they enhance Foxp3 expression as well as inhibit the effect of the proinflammatory cytokine IL-6 on Foxp3 regulation and function. How epigenetic mechanisms work under different inflammatory and tolerance conditions and regulate Foxp3 expression are fertile areas for further investigation. Understanding what cytokines and surface receptors are involved in the epigenetic regulation of Treg development and function will provide a better approach to generate Tregs for therapeutic use. Global genome-wide analysis of epigenetic markers in Tregs will enrich our ability to design epigenetic therapy. A future challenge is the development of cell type–specific targeting of DNMTs and HDACs to provide better epigenetic therapeutics.

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Epigenetic mechanisms of regulation of Foxp3 expression

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