



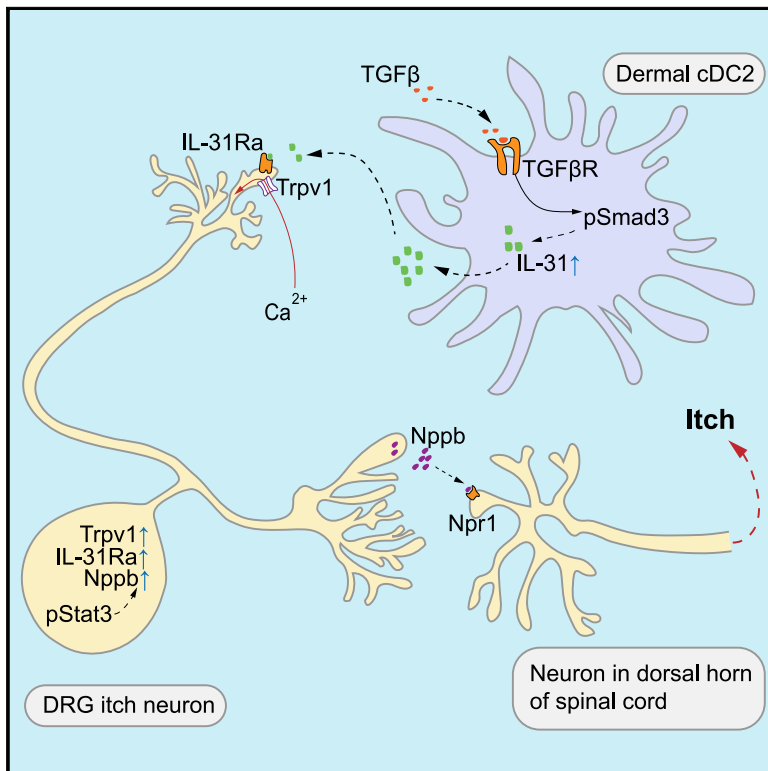
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## Immunity

# The Cytokine TGF- $\beta$ Induces Interleukin-31 Expression from Dermal Dendritic Cells to Activate Sensory Neurons and Stimulate Wound Itching

## Graphical Abstract



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## In Brief

Xu et al. find that TGF- $\beta$ , produced as part of the wound healing process, induces expression of interleukin-31 by dermal conventional type 2 DCs, which, in turn, increases neuron sensitivity and provokes itching.

## Highlights

- IL-31 expression is increased in skin wounds during the peak of itch response
- *Il31*<sup>-/-</sup> mice have less itch behavior during wound healing
- IL-31 increases calcium influx and *Il31ra*, *Trpv1* expression in itch sensory neurons
- TGF- $\beta$ 1 induces expression of IL-31 in dermal conventional type 2 dendritic cells



## Article

# The Cytokine TGF- $\beta$ Induces Interleukin-31 Expression from Dermal Dendritic Cells to Activate Sensory Neurons and Stimulate Wound Itching

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## SUMMARY

Cutaneous wound healing is associated with the unpleasant sensation of itching. Here we investigated the mechanisms underlying this type of itch, focusing on the contribution of soluble factors released during healing. We found high amounts of interleukin 31 (IL-31) in skin wound tissue during the peak of itch responses. *Il31*<sup>-/-</sup> mice lacked wound-induced itch responses. IL-31 was released by dermal conventional type 2 dendritic cells (cDC2s) recruited to wounds and increased itch sensory neuron sensitivity. Transfer of cDC2s isolated from late-stage wounds into healthy skin was sufficient to induce itching in a manner dependent on IL-31 expression. Addition of the cytokine TGF- $\beta$ 1, which promotes wound healing, to dermal DCs *in vitro* was sufficient to induce *Il31* expression, and *Tgfb1*<sup>fl/fl</sup> CD11c-Cre mice exhibited reduced scratching and decreased *Il31* expression in wounds *in vivo*. Thus, cDC2s promote itching during skin wound healing via a TGF- $\beta$ -IL-31 axis with implications for treatment of wound itching.

## INTRODUCTION

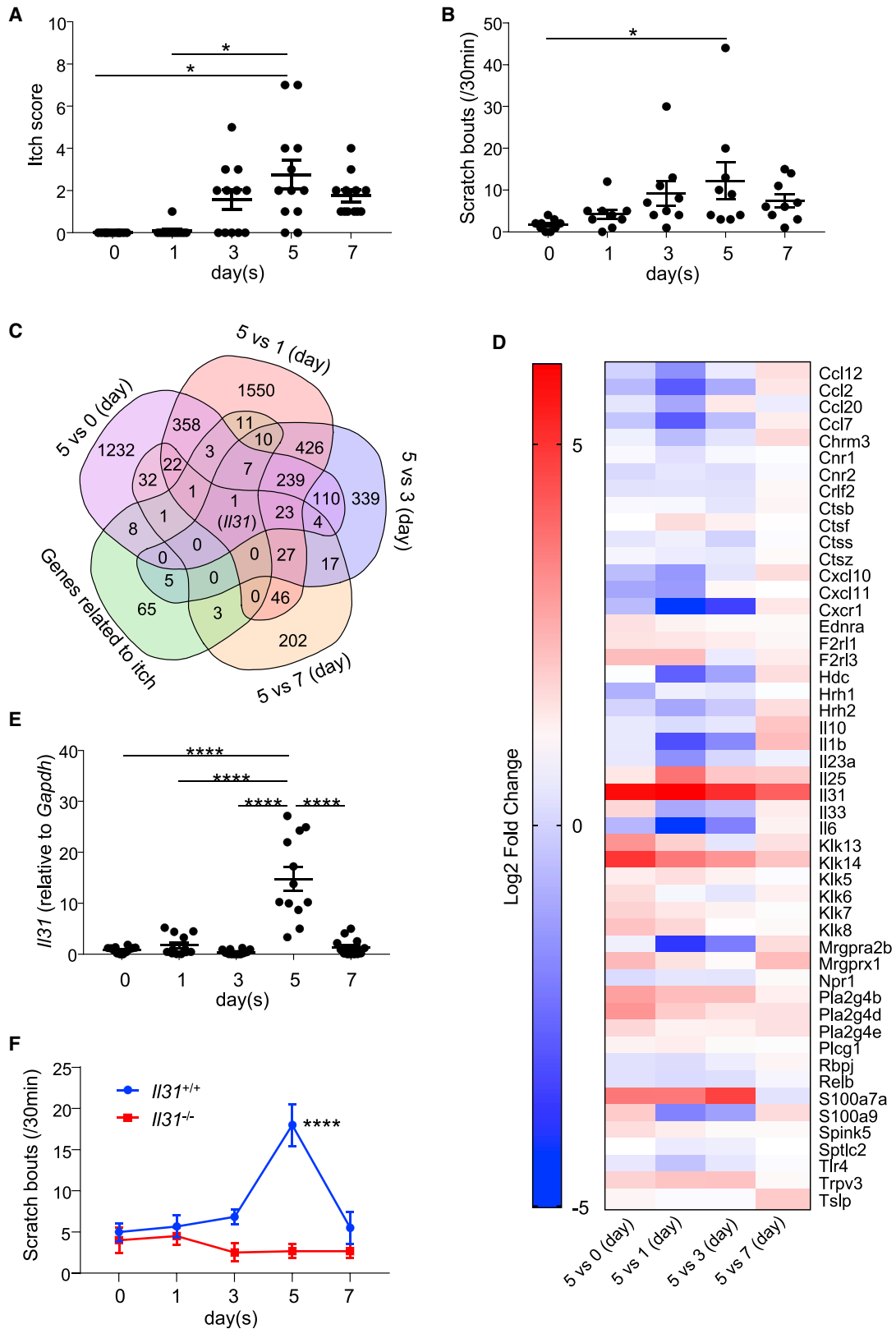
Cutaneous wound healing is a highly coordinated process that includes production of an ordered and dynamic inflammatory response involving multiple growth factors and cytokines (Ashcroft et al., 1999; Keyes et al., 2016; Massagué, 1999; Ross and Odland, 1968). For most wounds, itching is an unpleasant symptom that arises in the latter part of the healing process. Clinically, in patients with more extensive wounds (e.g., burns), there is more severe and persistent itching (Prasad et al., 2019; Parnell et al., 2012). Chemically induced itching is evoked by pruritogens activating primary afferent sensory neurons, which innervate the skin and have cell bodies in dorsal root ganglia (DRGs) and trigeminal ganglia. In mice, itch-inducing agents are detected by two nonoverlapping classes of sensory neurons that are thought, in part, to use the ion channel transient receptor potential cation channel subfamily V, member 1 (TRPV1) (Imamachi et al., 2009; Shim et al., 2007). One of these classes of neurons is marked by the transmitter natriuretic polypeptide B (NPPB) (Mishra and Hoon, 2013), which may convey pruritic signals to spinal cord circuits. The second class of neurons is defined by expression of Mas-related G-protein-coupled receptor  $\alpha$ 3 (Mrgpra3; Han et al., 2013), which express several

itch receptors, including Mrgpra3 and Mrgprc11. Activation of Nppb is sufficient to generate itch behavior (Huang et al., 2018) and is required for interleukin-31 (IL-31)-induced itching (Solinski et al., 2019b).

The interaction between the nervous system and the immune system has been suggested to be critically involved in normal homeostasis and pathogenic processes (Chavan et al., 2017). It has also become increasingly clear that neurological systems regulate immune responses through cell-cell contact (Tian et al., 2009) and/or release of soluble factors (Chavan et al., 2017). However, few studies have investigated the reverse direction; i.e., regulation of sensory neurons by the immune system. Specific inflammatory cytokines have been suggested to influence itching in skin (Bautista et al., 2014; Jin et al., 2009; Oetjen et al., 2017), suggesting that inflammation in the skin might play a role in development and pathogenesis of itching. However, the primary factor(s) and the underlying mechanisms of immune-mediated itching during wound healing remain elusive.

Here we utilized an experimental mouse model of wound healing to investigate the effects of immune responses on itching. We showed that IL-31, a prominent cytokine implicated previously in itching (Cevikbas et al., 2014; Dillon et al., 2004), was upregulated in skin wound tissue on the fifth day of healing, when itch





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responses are maximal. We confirmed the itch-promoting effects of IL-31 on the skin and elucidated that IL-31 increased expression of the transduction channel TRPV1 and potentiated calcium influx in DRG neurons. Importantly, we also showed that the major cellular source of IL-31 production is dermal conventional type 2 dendritic cells (cDC2s).

## RESULTS

### Itch Responses and Changes in IL-31 Expression Follow Similar Time Courses during Wound Repair

To determine the progression of itch responses during skin wound healing, we monitored pruritus elicited by acute wound healing in humans and mice. For human subjects, we evaluated pruritus in 12 patients (diagnosed with a superficial cyst or benign tumor) using questionnaires for pruritus self-assessment prior to and every other day after surgery, employing a 10-cm visual analog scale (VAS; see STAR Methods for details). We observed that, in most patients, pruritus reached a peak on the fifth day after surgery (Figure 1A). Next we used an experimental mouse model of skin wound healing (Ashcroft et al., 2000; Figure S1) and found that, similar to humans, mouse scratching responses (Video S1) were maximal on the fifth day of healing (Figure 1B).

To investigate whether there are soluble factor(s) present in wounded skin produced by immune cells during wound healing, which might be responsible for itching, we collected tissue and sequenced RNA transcripts several times before and during wound healing. For an unbiased analysis, we examined RNA sequencing (RNA-seq) reads, exploring changes in expression of all genes and focusing on those whose expression changes over the course of the healing process. We hypothesized that the expression of factors contributing to itching would peak at about the same time as itch responses. Next we examined genes, based on published literature (Bautista et al., 2014; Nattkemper et al., 2018; Table S1), that might be involved in this process. Using these criteria, we uncovered IL-31 as a candidate for induction of itching after cutaneous incision (Figures 1C and 1D; Table S2). Confirming our RNA-seq analysis, real-time quantitative polymerase chain reaction (qPCR) and ELISA showed that there was increased expression of IL-31 throughout wound healing that peaked on day 5 after incision (Figure 1E; Figure S2A).

### IL-31 Is Responsible for Itch Responses during Wound Healing

If IL-31 is responsible for itch responses during wound healing, then we predicted that administration of additional IL-31 should further potentiate these responses. To test this, we injected IL-31 (30 ng/site, intradermally [i.d.]) into wounds starting on day 4 (see STAR Methods for details). In line with our hypothesis, mice treated with additional IL-31 displayed a higher number of scratching bouts compared with untreated animals (Figure S2B). To further investigate the role of IL-31 in itching during wound healing, we used *Il31*<sup>-/-</sup> mice (Figure S2C). Corroborating a role of IL-31 in wound-induced itching, *Il31*<sup>-/-</sup> mice scratched much less than wild-type mice on day 5 of wound healing (Figure 1F). A similar phenomenon was observed when bone marrow from *Il31*<sup>-/-</sup> mice was transferred into irradiated C57BL/6 recipients (Figures S2D and S2E), indicating that hematopoietic cells, and possibly leukocytes, might be the main source of secreted IL-31.

### IL-31 Increases Itch Sensory Neuron Sensitivity

Next, using RT-PCR, we compared the gene expression of molecules associated with signal transduction in DRGs that innervate the wound site between baseline and 5 days after incision. This comparison uncovered that expressions of *Il31ra*, *Trpv1*, and *Nppb* was upregulated during healing in sensory neurons, whereas expression of *Trpa1* did not change significantly (Figures S3A–S3D). Because DRG neurons are a heterogeneous population, *Trpv1*-lineage reporter mice (*Trpv1*-tdTomato mice) were also used to enrich for transcripts present in itch sensory neurons (Mishra et al., 2011). qPCR showed that *Il31ra*, *Trpv1*, and *Nppb* (Figures 2A–2C) were upregulated in sorted DRGs of *Trpv1*-lineage mice (which innervate wounds on day 5 after incision). This result is consistent with IL-31 being involved in induction of increased itch sensitivity in sensory neurons. To further test this hypothesis, we treated mouse DRG sensory neurons *in vitro* with IL-31. We found that IL-31 treatment on its own was sufficient to induce upregulation of *Trpv1*, *Il31ra*, and *Nppb* expression (Figures S3E–S3G). In addition, IL-31 treatment for 24 h could potentiate capsaicin (50 nM)-stimulated calcium influx in cultured DRG neurons (Figures 2D, S3H, and S3I) and could slightly increase the number of capsaicin-responding neurons in functional assays (Figure S3J). These results suggest that IL-31 may increase the expression of key signal transduction molecules in sensory neurons and that it can sensitize these nerves.

#### Figure 1. Pruritus Elicited by Acute Wound Healing and IL-31 Is Important for Itch during Wound Healing

(A) 12 patients with 1- to 3-cm sterile surgical wounds who experienced pruritus were surveyed over 7 days and asked to score the level of itching they felt on each day. One-way ANOVA was used for comparisons. Bars represent means  $\pm$  SEM. \* $p < 0.05$ .

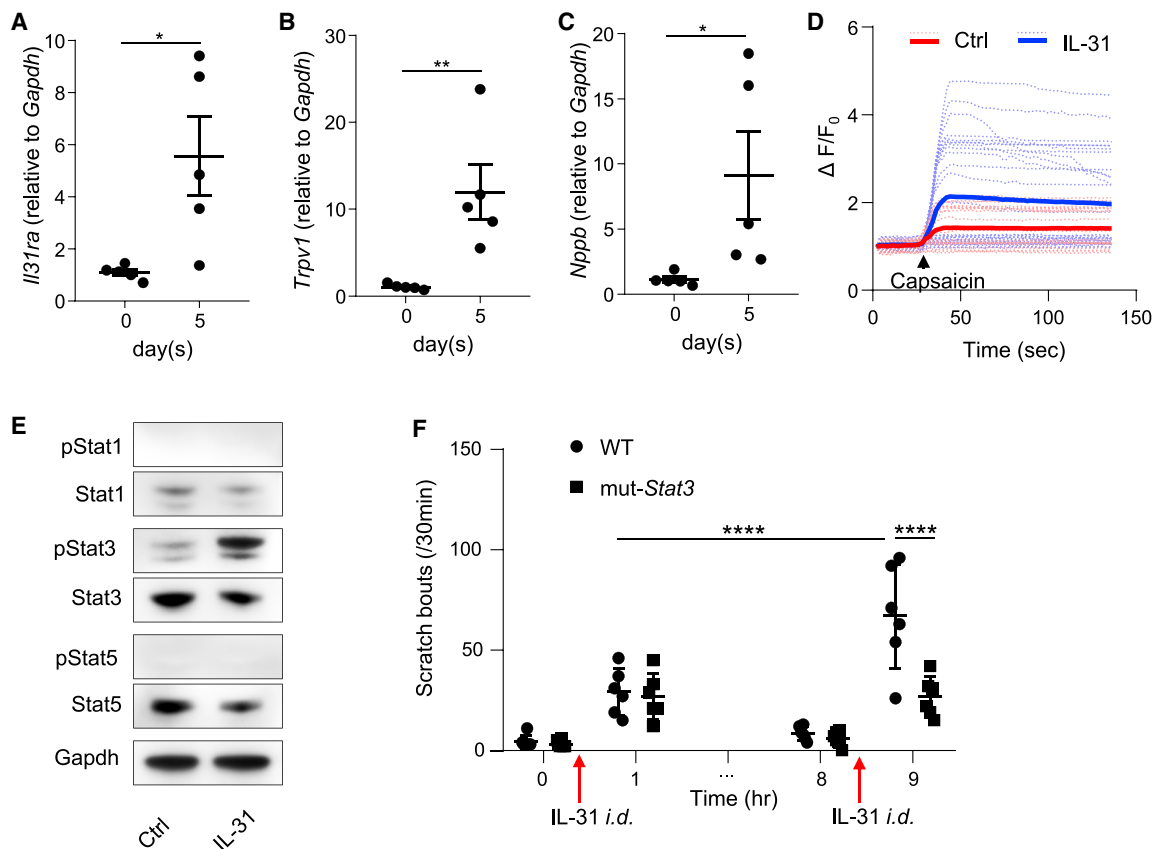
(B) A mouse wound healing model was established by making 2 equidistant, 1 cm, full-thickness incisional wounds through the dorsal skin and left to heal. The number of scratching bouts per 30 min of observation were measured for 7 days following wounding. Data are from 3 independent experiments ( $n = 9$ ) and were analyzed with a one-way ANOVA for comparisons. Bars represent means  $\pm$  SEM. \* $p < 0.05$ .

(C and D) Mouse wound skin at different time points was harvested, followed by RNA-seq of the mRNAs. The Venn diagram (C) shows overlapping of the genes that were significantly changed ( $p < 0.01$ ) on the fifth day versus other time points of wound healing and genes related to itching based on published literature. The heatmap (D) shows all the itch-associated genes which changed on the fifth day were compared with any other time points. For RNA-seq, 2 wound tissues from one animal were pooled, and 3 animals were used per time point.

(E) The expression of IL-31 in wounds was confirmed by qPCR. Data are from 3 independent duplicated experiments ( $n = 12$ ) and were analyzed with a one-way ANOVA for comparisons. Bars represent means  $\pm$  SEM. \*\*\*\* $p < 0.0001$ .

(F) Itching behaviors of *Il31*<sup>-/-</sup> mice during wound healing were compared with wild-type mice. Data are pooled from 2 independent experiments ( $n = 6$ ) and represented as mean  $\pm$  SEM; two-way ANOVA was used. \*\*\*\* $p < 0.0001$ .

See also Figure S2 and Tables S1 and S2 for more details.



**Figure 2. IL-31 Increases Itch Sensory Neuron Sensitivity**

(A–C) TRPV1+ cells from DRGs that innervate the fifth day's wounds in *Trpv1*-lineage reporter mice (*Trpv1*-tdTomato mice) were sorted by flow cytometry, and the expression of *Il31ra* (A), *Trpv1* (B), and *Nppb* (C) in these TRPV1+ cells that innervate the fifth day's wounds were compared with TRPV1+ cells that innervate naive skin in normal controls by qPCR. Data were from 2 independent experiments ( $n = 5$ ), and each sample was pooled from 2 mice. Student's *t* test was used for comparisons. Bars represent means  $\pm$  SEM. \* $p < 0.05$ , \*\* $p < 0.01$ .

(D) The calcium transient in capsaicin (50 nM) was observed in DRG neurons treated with IL-31 (10 ng/mL) for 24 h and in untreated neurons. The solid blue and red lines were representative images (mean values) and dash lines were individual traces.

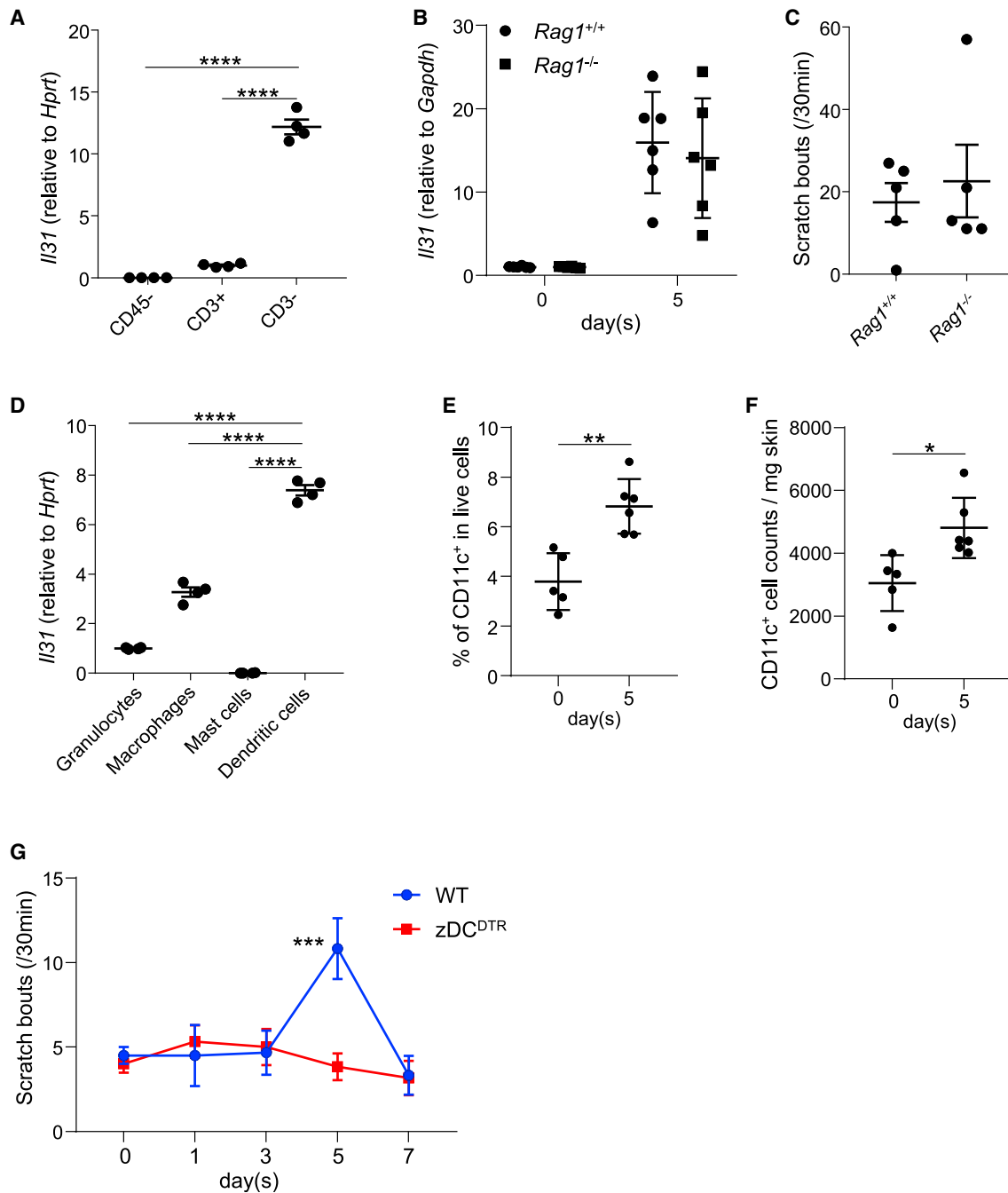
(E) Phosphorylation of Stat3 was detected by western blot in DRG neurons treated with IL-31 (10 ng/mL) for 24 h. Data are representative of 3 independent experiments.

(F) Scratching bouts of *mut-Stat3* mice were counted after the first IL-31 injection (1  $\mu$ g/site, i.d.) and compared with wild-type mice. 8 h after the first IL-31 injection, the second IL-31 injection was administered, and the itching behaviors were again observed. Data were from 2 independent experiments ( $n = 6$ ) and analyzed with a two-way ANOVA for comparisons. Bars represent means  $\pm$  SEM. \*\*\*\* $p < 0.0001$ .

See also [Figure S3](#) for more details.

Because IL-31, via the IL-31ra receptor, may induce changes in gene expression and neural activity through a Jak1-mediated pathway (Zhang et al., 2008), we investigated potential additional downstream effectors of IL-31 activation. To do this, we explored, in DRG neurons, which Stat molecules might be regulated by IL-31 treatment. These experiments revealed that IL-31 induces phosphorylation of Stat3 (Figure 2E). If Stat3 phosphorylation is required for potentiation of neuronal activity, then administration of a specific Stat3 inhibitor should attenuate IL-31-induced increases in calcium responses to capsaicin. Indeed, the Stat3 inhibitor S31-201 blocked IL-31-stimulated increases in calcium influx and the numbers of neurons responding to capsaicin (Figures S3K–S3M). Furthermore, S31-201 inhibited IL-31-induced upregulation of *Trpv1* and *Il31ra* expression (Figures S3N and S3O), indicating that these IL-31-mediated effects are Stat3 dependent.

We wondered how IL-31 acts on itch sensory neurons to alter gene expression. To investigate this, we tested the effects of IL-31 on neurons at different time points. We uncovered that Stat3 phosphorylation occurred within 15 min after IL-31 treatment (Figure S3P), but the increase in *Il31ra* and *Trpv1* expression was delayed and started between 1 and 3 h later (Figures S3Q and S3R). Furthermore, when we injected IL-31 (1  $\mu$ g/site i.d.) into mutant (*mut-Stat3*) mice, the same amount of initial scratching was observed in *mut-Stat3* mice as in wild-type control mice. However, 8 h after the first IL-31 injection, when we gave a second IL-31 dose, scratching was increased markedly in wild-type mice but not in *mut-Stat3* animals (Figure 2F). In addition, concordant with results from our experiments with a Stat3 inhibitor, *Il31ra* and *Trpv1* gene expression in DRGs that innervate the injected area of skin also showed that IL-31 injection *in vivo* could not upregulate these two genes in the short



**Figure 3. Dermal DCs Are a Key Source of IL-31 in Wounds**

(A) *Il31* gene expression was determined in CD45<sup>-</sup> cells, CD45<sup>+</sup>CD3<sup>+</sup> cells, and CD45<sup>+</sup>CD3<sup>-</sup> cells sorted from fifth-day wounds tissue by qPCR. Data were from 2 independent experiments with 2 samples each time, and each sample was pooled from 4 wounds in 2 mice. Data were analyzed with one-way ANOVA for comparisons. Bars represent means  $\pm$  SEM. \*\*\*\* $p < 0.0001$ .

(B) Expression of IL-31 in wounds on the fifth day were tested in *Rag1*<sup>-/-</sup> mice and wild-type mice by real-time PCR. Data are from 3 independent experiments ( $n = 6$ ), and two-way ANOVA was used for comparison. Bars represent means  $\pm$  SEM.

(C) Scratching behaviors were observed in *Rag1*<sup>-/-</sup> mice before and on the fifth day of wound healing. Data are from 2 independent experiments ( $n = 5$ ); Student's *t* test was used. Bars represent means  $\pm$  SEM.

(D) DCs (CD45<sup>+</sup>CD3<sup>-</sup>CD11c<sup>+</sup>MHC II<sup>+</sup>), macrophages (CD45<sup>+</sup>CD3<sup>-</sup>CD11c<sup>-</sup>CD11b<sup>+</sup>F4/80<sup>+</sup>), granulocytes (CD45<sup>+</sup>CD3<sup>-</sup>CD11c<sup>-</sup>CD11b<sup>+</sup>F4/80<sup>-</sup>), and mast cells (CD45<sup>+</sup>CD3<sup>-</sup>CD11c<sup>-</sup>CD11b<sup>-</sup>FcεR1a<sup>+</sup>) were sorted from fifth-day wounds, and the expression of *Il31* was determined by real-time PCR. Data were from 2 independent experiments with 2 samples each time, and each sample was pooled from 4 wounds in 2 mice. Data were analyzed with one-way ANOVA for comparisons. Bars represent means  $\pm$  SEM. \*\*\*\* $p < 0.0001$ .

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term (within 1 h) but could increase expression over the long term (8 h) in wild-type mice (Figures S3S and S3T). Notably, this IL-31-induced upregulation did not occur in *mut-Stat3* mice (Figures S3S and S3T). Furthermore, to investigate whether scratching during wound healing is associated with Nppb/Npr1, we injected an Nppb receptor agonist, Npr1 (JS-11, 5 mg/kg intraperitoneally [i.p.]) into mice on day 5 of wound healing (Solinski et al., 2019a). JS-11-treated mice exhibited attenuated scratching 15 min after injection (Figure S3U), indicating that the wound-associated itch is Nppb/Npr1 dependent. Taken together, our results suggest that IL-31 has short-term effects that are Stat3 independent and has longer-term effects on neuronal sensitivity, as evidenced by Stat3-dependent increased *Il31ra* and *Trpv1* expression.

### Dendritic Cells Cause Itching during Wound Healing

We next investigated the source of IL-31 in the skin during wound healing. IL-31 has been classified as a T helper 2 (Th2) cytokine (Dillon et al., 2004); however, CD3<sup>+</sup> T cells sorted from wound tissues on day 5 after incision expressed much lower *Il31* than CD3<sup>-</sup> non-T cells within the CD45<sup>+</sup> immune cell population (Figure 3A). Our analysis also revealed that CD45<sup>-</sup> non-immune cells expressed minimal *Il31* mRNA (Figure 3A). Confirming these results, the expression of IL-31 detected in wounds from *Rag1*<sup>-/-</sup> mice was the same as in control mice (Figures 3B and S4A), indicating that T cells or B cells are not a major source of IL-31 in wounds. Again, in line with B and T cells having minimal involvement in wound itching, *Rag1*<sup>-/-</sup> mice exhibited similar wound-induced scratch behaviors as wild-type mice (Figure 3C). When we further fractionated CD3<sup>-</sup> non-T cells from wound skin, we found that dendritic cells (DCs) had higher expression of *Il31* compared with macrophages, granulocytes, and mast cells (Figure 3D). Moreover, higher numbers of CD11c<sup>+</sup> cells were found in day 5 wounds compared with normal skin (Figures 3E, 3F, and S4B).

If DCs are the major source of IL-31 in wounds, then depletion of DCs in the skin should alleviate itching during wound healing. To test this, we made a previously characterized cDC depletion mouse model (Meredith et al., 2012) by transferring bone marrow from zDC<sup>DTR</sup> mice, in which human diphtheria toxin receptor is expressed in cDCs, but not monocytes or other immune cell populations, into irradiated C57BL/6 hosts and injecting diphtheria toxin (DT) to specifically deplete cDCs (Figure S4C). These mice did not exhibit increased itch behavior during wound healing (Figure 3G), indicating that cDCs may be the main source of IL-31. Furthermore, *Il31* expression in the wounds of these mice was also lower than in control animals (Figure S4E), but these mice displayed no change in wound closure and healing (Figure S4D). These results establish that DCs are the primary source of IL-31, which causes itching during wound healing.

### cDC2s Are a Key Source of IL-31 in Wounds

To determine which subset of DCs express IL-31, we next sorted Langerhans cells (LCs), type 1 cDCs (cDC1s), cDC2s, as well as macrophages and found that cDC2s expressed the highest level of *Il31* of all of these types of cells (Figure 4A). We further used *Lang*<sup>DTR</sup> mice, which express the human DT receptor (DTR) downstream of the internal stop codon of the *Langerin* gene, to deplete LCs (Figures S5A–S5C). We also used a well-characterized monocyte/macrophage depletion mouse model by crossing *Lys2*<sup>Cre</sup> mice and *Csf1r*<sup>DTR</sup> mice (Schreiber et al., 2013) (hereafter called MM<sup>DTR</sup> mice). In *Csf1r*<sup>DTR</sup> mice, a DTR preceded by a loxP-flanked transcriptional stop element under control of the *Csf1r* promoter, expression of *Cre* recombinase excises the stop element and allows transcription and translation of DTR in cells expressing *Csf1r*, so administering DT to MM<sup>DTR</sup> mice could deplete macrophages in the skin (Figures S5D–S5F). Itch behaviors during wound healing in these two models were observed. Both models have normal frequencies of cDCs in the skin (Figures S5A and S5D) and normal itch behavior on day 5 during wound healing. We also compared *Il31* expression between dermal cDC1s and cDC2s by using CD103 and CD207 as markers to distinguish dermal cDC1s and cDC2s (Kashem et al., 2017) and found that dermal cDC2s indeed expressed higher levels of *Il31* than cDC1 (Figures S5G and S5H). Moreover, *Il31* mRNA expression in cDC2s from day 5 wounds was much higher than in cDC2s from normal skin (Figure 4B). The proportions (Figures 4C and 4D) and total numbers of cDC2s (Figure 4E) were also increased on day 5 after incision compared with naive skin.

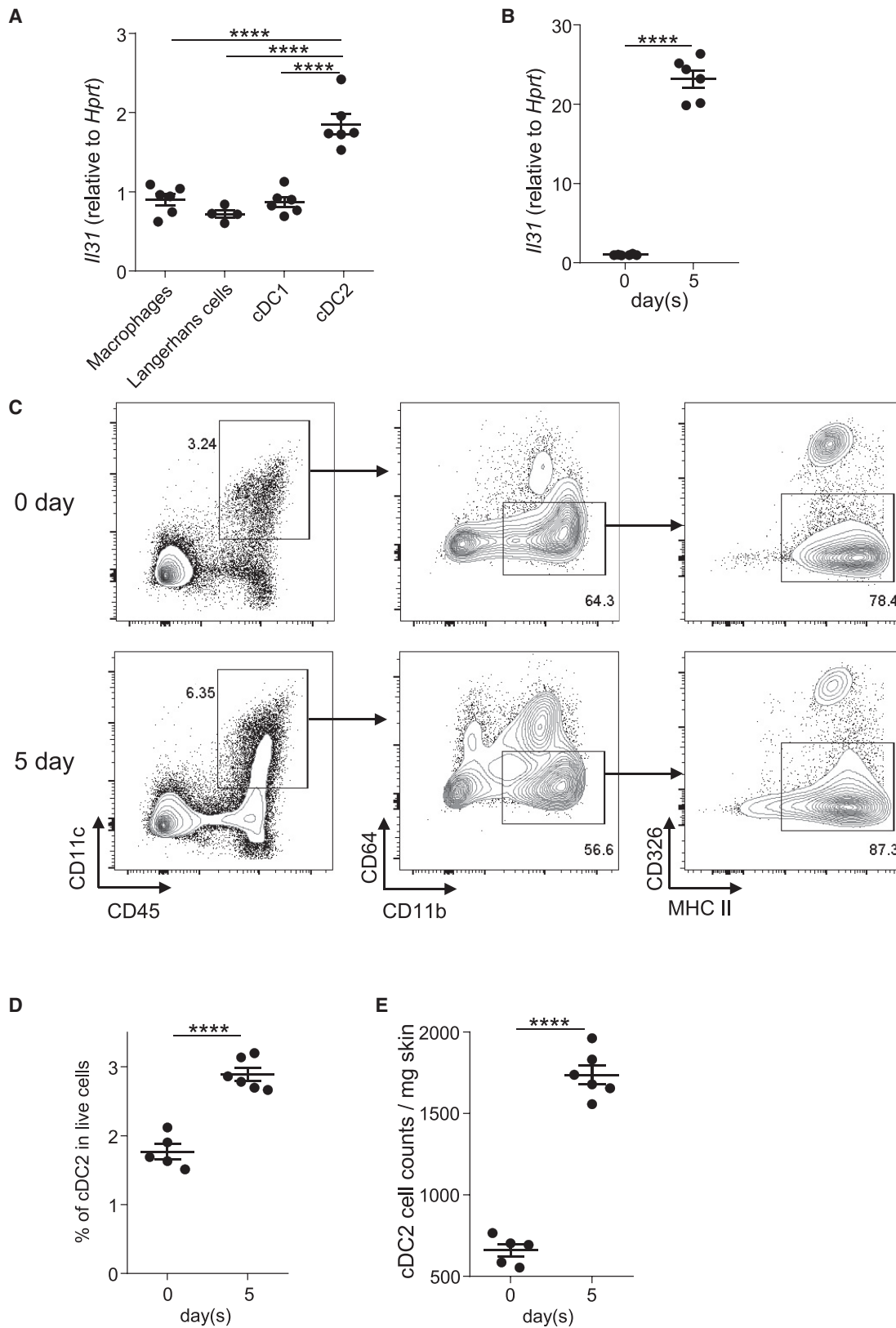
These results suggest that cDC2s are the likely source of *Il31*, producing increased scratching during wound healing. To further validate this, we examined whether cDC2s are sufficient to elicit wound-like itching. We purified cDC2s from day 5 wounds or normal skin and injected them intradermally in uninjured recipient mice (1.5 × 10<sup>4</sup> cells per site). cDC2s from wound sites increased scratching in recipient mice 3 h after injection (Video S2) but cDC2s from normal skin did not (Figure 5A). In addition, consistent with these cDC2s evoking itching through activation of an IL-31 process, expression of *Il31ra* (Figure 5B), *Trpv1* (Figure 5C), and *Nppb* (Figure 5D) was upregulated in DRGs of recipient mice that innervated the skin around cDC2 injection. To probe whether scratching evoked by dermal cDC2 administration elicits itching or nociceptive sensations, we turned to the cheek model (Shimada and LaMotte, 2008). In this model, scratch responses to intradermal injection of a substance into the face are interpreted to be caused by itching, whereas wipe responses are believed to be triggered by nociception (production of pain). Consistent with cDCs provoking itching, injection of cDC2s from day 5 of wound healing into the cheek caused prominent scratching compared with cDCs from naive mice (Figure 5E). In contrast, wiping responses were similar for cDCs from

(E and F) The frequency (E) and numbers (F) of CD11c<sup>+</sup> cells from day 5 wounds was calculated and compared with those from normal skin. Data were from 3 independent experiments (n = 5–6), analyzed with Student's t test for comparisons. Bars represent means ± SEM. \*\*\*\*p < 0.0001.

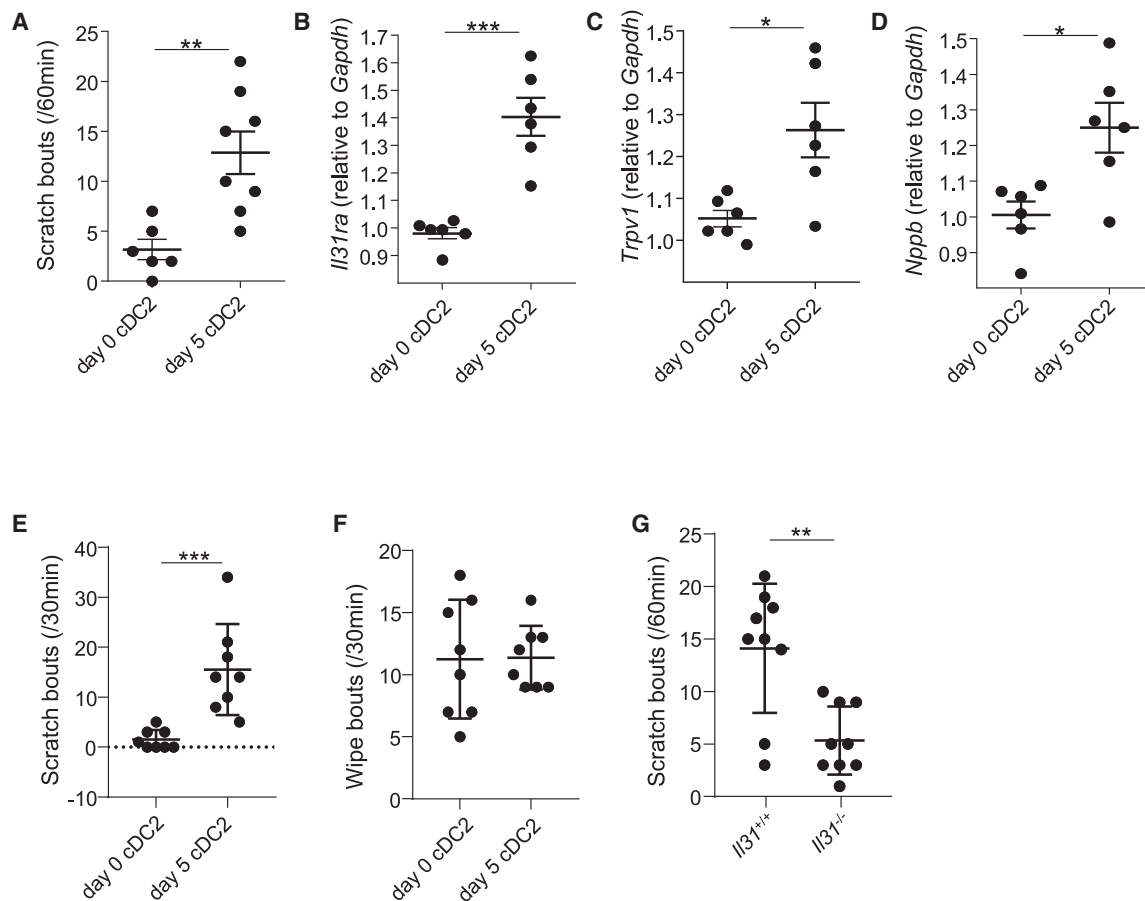
(G) Itching behaviors during wound healing were observed in diphtheria toxin (DT)-treated (i.p., 500 ng/mouse for the first time and 100 ng/mouse on all subsequent days) zDC<sup>DTR</sup>-to-C57BL/6 bone marrow chimera mice and were compared with DT-treated C57BL/6-to-C57BL/6 bone marrow chimera mice (WT [wild-type]). Data were pooled from 6 mice for each condition in two independent experiments and are represented as mean ± SEM. Two-way ANOVA was used for multiple comparisons. \*\*\*p < 0.001.

See also Figure S4 for more details.





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**Figure 5. Administration of Late Wound Stage Dermal cDC2s Evokes Itch Responses**

(A–D) Dermal cDC2s sorted from fifth-day wounds or normal skin was injected intradermally to the dorsal area of normal B6 mice at 15,000 per site, and the scratching behaviors were counted 3 h after injection (A). The expression of *Il31ra* (B), *Trpv1* (C), and *Nppb* (D) in DRGs that innervate the back skin around the dermal cDC2-injected area was also determined by real-time PCR. Data were from 2 independent experiments with 3–4 mice each time. Student's t test was used for comparison. Bars represent means  $\pm$  SEM. \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ .

(E and F) The numbers of scratching behaviors (E) and wiping behaviors (F) were counted after injection of cDC2s from fifth-day wounds or normal skin to cheeks of mice. Each circle represents one mouse. Data are from 2 independent experiments ( $n = 8$ ), and Student's t test was used. Bars represent means  $\pm$  SEM. \*\*\* $p < 0.001$ .

(G) Scratching bouts were counted in recipient mice that were injected with cDC2s from fifth-day wounds of *Il31*<sup>-/-</sup> mice or WT mice. Data were pooled from 3 independent experiments ( $n = 9$ ). Each circle represents one mouse. Student's t test was used. Bars represent means  $\pm$  SEM. \*\* $p < 0.01$ . See also Figure S5 for more information.

naive and day 5 wounds (Figure 5F). Supporting this conclusion itch responses evoked by day 5 wound cDC2s from *Il31*<sup>-/-</sup> mice were similar to the behavior elicited by administration of cDC2s from naive skin (Figure 5G). Taken together, these results suggest that cDC2 is the major source of IL-31 in wounds, which produces itching associated with wound repair.

### TGF- $\beta$ Increases IL-31 in Dermal cDC2s

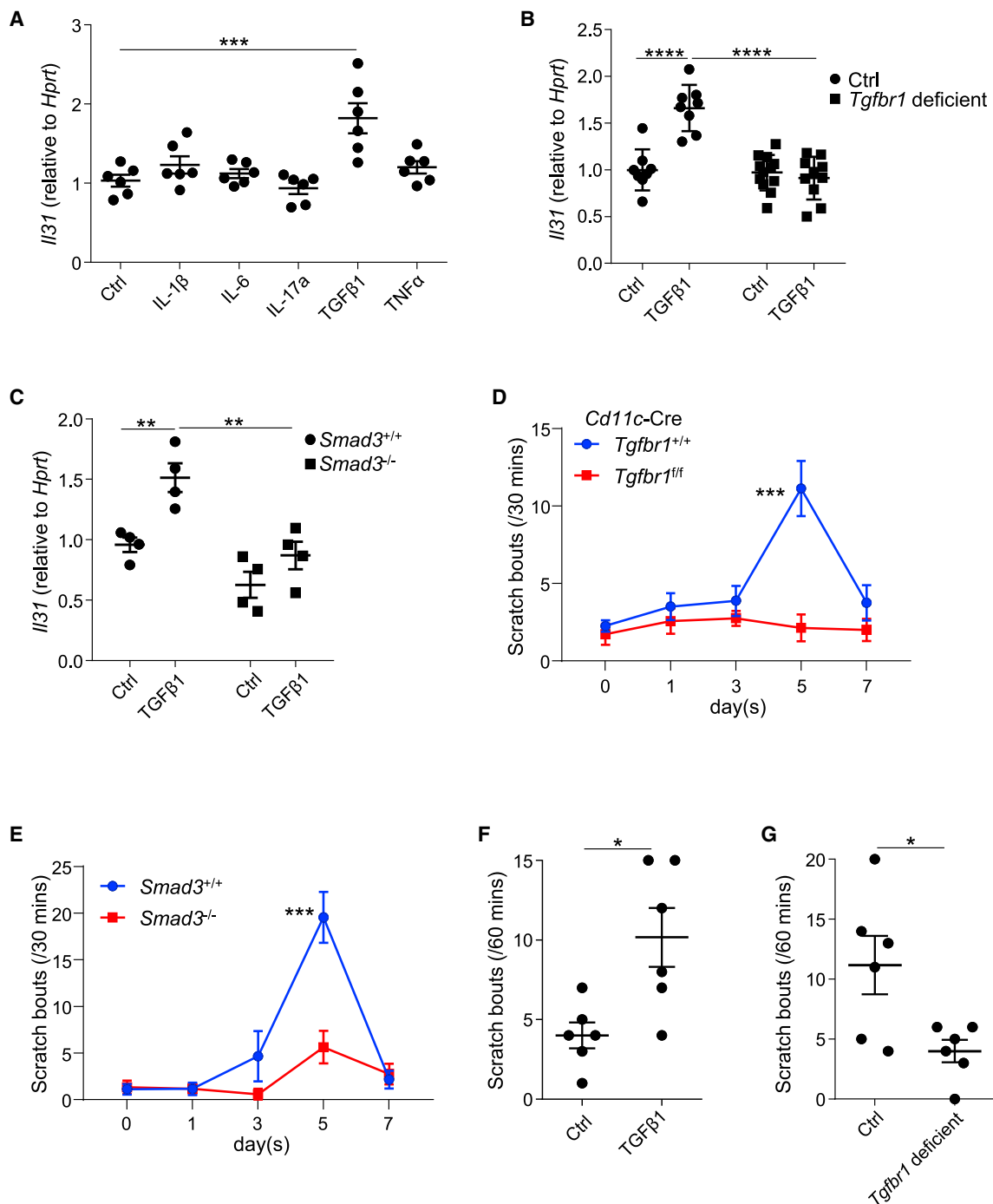
Because cDC2s in healthy skin contain low amounts of IL-31, we wondered which cues in wounds might be involved in increasing its expression. The cytokines IL-1 $\beta$ , IL-6, IL-17a, transforming growth factor  $\beta$ 1 (TGF- $\beta$ 1), and tumor necrosis factor alpha (TNF- $\alpha$ ) have been reported to be important participants in

**Figure 4. IL-31 in Wounds Was Mostly from Dermal cDC2s**

(A) Macrophages (CD45<sup>+</sup>CD3<sup>-</sup>CD11c<sup>-</sup>CD64<sup>+</sup>CD11b<sup>+</sup>F4/80<sup>+</sup>), LCs (CD45<sup>+</sup>CD3<sup>-</sup>CD11c<sup>+</sup>CD326<sup>+</sup>), dermal cDC2s (CD45<sup>+</sup>CD3<sup>-</sup>CD11c<sup>+</sup>CD326<sup>-</sup>CD64<sup>-</sup>CD11b<sup>+</sup>MHC II<sup>+</sup>), and dermal cDC1s (CD3<sup>-</sup>CD11c<sup>+</sup>CD326<sup>-</sup>CD64<sup>-</sup>CD11b<sup>-</sup>MHC II<sup>+</sup>) were sorted from fifth-day wounds, and *Il31* expression was determined by real-time PCR. Data were from 2–3 independent experiments with 2 samples each time, and each sample was pooled from 4 wounds in 2 mice. Data were analyzed with one-way ANOVA for comparisons. Bars represent means  $\pm$  SEM. \*\*\*\* $p < 0.0001$ .

(B) *Il31* gene expression in dermal cDC2 from fifth-day wounds was compared with cDC2s from normal skin by real-time PCR. Data are from 3 independent experiments with 2 samples each time, and each sample was pooled from 4 wounds in 2 mice. Data were analyzed with Student's t test for comparisons. Bars represent means  $\pm$  SEM. \*\*\*\* $p < 0.0001$ .

(C–E) Flow cytometer analysis showed that the frequency (C and D) and total numbers of dermal cDC2s (CD45<sup>+</sup>CD11c<sup>+</sup>CD64<sup>-</sup>CD11b<sup>+</sup>MHC II<sup>+</sup>CD326<sup>-</sup>) (E) were increased in fifth-day wound skin tissues compared with normal skin. In (D) and (E), each circle represents one mouse. Data were from 3 independent experiments ( $n = 5$ –6), and Student's t test was used. Bars represent means  $\pm$  SEM. \*\*\*\* $p < 0.0001$ .



**Figure 6. TGF- $\beta$  Increases IL-31 in Dermal cDC2**

(A) IL-1 $\beta$  (10 ng/mL), IL-6 (50 ng/mL), IL-17a (10 ng/mL), TGF- $\beta$ 1 (2 ng/mL), and TNF- $\alpha$  (10 ng/mL) were used *in vitro* to treat cDC2s sorted from healthy skin individually, and *Il31* expression in dermal cDC2s was determined 6 h after treatment. Data were from 3 independent experiments (n = 6), and each circle represents one culture well. Data were analyzed with one-way ANOVA for comparisons. Bars represent means  $\pm$  SEM. \*\*\*p < 0.001.

(B and C) The expression of *Il31* in TGF- $\beta$ 1-treated dermal cDC2s from *Tgfr1*-deficient mice (tamoxifen-treated *Tgfr1<sup>fl/fl</sup> Ert2-Cre* mice) (B) and *Smad3<sup>-/-</sup>* mice (C) were determined and compared with WT dermal cDC2s. Data were from 2 independent experiments (n = 4–8). Each circle represents one culture well, and two-way ANOVA was used for comparisons. Bars represent means  $\pm$  SEM. \*\*\*\*p < 0.0001.

(D and E) The wound healing model was set up in *Tgfr1<sup>fl/fl</sup> Cd11c-Cre* (D) and *Smad3<sup>-/-</sup>* mice (E). Itching behaviors were observed in *Tgfr1<sup>fl/fl</sup> Cd11c-Cre* mice and *Smad3<sup>-/-</sup>* mice and compared with WT controls. Data were from 3 independent experiments (n = 6–8) and represented as mean  $\pm$  SEM. Two-way ANOVA was used for comparisons. \*\*\*p < 0.001.

(legend continued on next page)

coordinating wound repair (Barrientos et al., 2008; Mast and Schultz, 1996). Therefore, we tested the effects of these cytokines on induction of IL-31 expression in isolated dermal cDC2s *in vitro*. Unexpectedly, only TGF- $\beta$ 1 substantially increased *Il31* expression in cDC2s from normal skin (Figure 6A). Consistent with TGF- $\beta$ 1 inducing IL-31 in dermal cDC2s, we found that TGF- $\beta$ 1 expression was raised between days 3 and 5 after incision (Figure S6A). Because Smad3 is downstream of canonical TGF- $\beta$  signaling, we used a TGF- $\beta$  receptor I (TGF- $\beta$ RI) inhibitor (SB431542) or a selective Smad3 inhibitor (SIS3) under TGF- $\beta$ 1 culture conditions. Corroborating TGF- $\beta$ RI and Smad3 as being part of the signal cascade for induction of *Il31* expression, their inhibitors reduced induction of IL-31 transcription (Figure S6B). Further substantiating the contribution of TGF- $\beta$  in induction of IL-31 expression, the increase in *Il31* expression in response to TGF- $\beta$  is absent in dermal cDC2s from TGF- $\beta$ RI global knockout mice (*Tgfb1<sup>fl/fl</sup> Ert2-Cre*) (Figure 6B) and *Smad3<sup>-/-</sup>* mice (Figure 6C), and *in vitro* TGF- $\beta$ 1 treatment failed to increase *Il31* expression in dermal cDC2s from these knockout mice (Figures 6B and 6C). To further investigate the role of TGF- $\beta$ RI in DCs during wound healing, we crossed *Cd11c-Cre<sup>+</sup>* mice with *Tgfb1<sup>fl/fl</sup>* mice to conditionally deplete TGF $\beta$ RI in DCs, whereas other types of cells were untouched. Histological staining showed that conditional depletion of TGF- $\beta$ RI in DCs did not alter the speed of the wound healing process (Figure S6C). Like the *Tgfb1<sup>fl/fl</sup> Ert2-Cre* mice, TGF- $\beta$ 1 treatment also failed to increase *Il31* expression in dermal cDC2s from *Tgfb1<sup>fl/fl</sup> CD11c-Cre* mice *in vitro* (Figure S6D). Compared with wild-type mice, *Tgfb1<sup>fl/fl</sup> CD11c-Cre* mice exhibited reduced scratching behaviors (Figure 6D) and a lower *Il31* expression in wounds (Figure S6E) on day 5 after injury. Notably, expression of *Il31ra* (Figure S6F), *Trpv1* (Figure S6G), and *Nppb* (Figure S6H) were also not upregulated in the DRGs that innervated wounds. Furthermore, we generated *Tgfb1<sup>fl/fl</sup> Lys2-Cre* mice, in which TGF- $\beta$ RI is eliminated on macrophages but not on DCs. These mice displayed a similar healing process and itching behaviors as wild-type mice (Figures S6J and S6K). Moreover, although the wound healing processes were accelerated (Figure S6L), scratch- and itch-related gene expression in *Smad3<sup>-/-</sup>* mice also declined relative to control littermates at all time points (Figures 6E and S6M–S6O). Finally, intradermal administration, in recipient animals, of TGF- $\beta$ 1-pretreated dermal cDC2s increased itch behavior ( $1.5 \times 10^4$  cells per site; Figure 6F). In contrast, TGF- $\beta$ 1-treated dermal cDC2s isolated from *Tgfb1<sup>fl/fl</sup> Ert2-Cre* mice (Figure 6G) and *Tgfb1<sup>fl/fl</sup> CD11c-Cre* mice (Figure S6I) failed to elicit itch responses. Moreover, even at a low dose of injection (5,000 cells per site), TGF- $\beta$ 1-treated dermal cDC2s could elicit itch responses (Figure S6P) and upregulate *Il31ra* gene expression in DRGs of recipient mice that innervated the skin injected with these cells, although no significant difference in *Trpv1* gene expression could be found (Figure S6Q),

whereas TGF- $\beta$ 1-treated dermal cDC2s from *Tgfb1<sup>fl/fl</sup> Ert2-Cre* mice failed to do so (Figures S6R and S6S). Together, these results demonstrate the crucial role of TGF- $\beta$  signaling in IL-31 production in dermal cDC2s during wound healing.

## DISCUSSION

In this study, we investigated the cellular and molecular mechanisms underlying itching during cutaneous wound healing, showing that TGF- $\beta$  induces expression of IL-31 in dermal cDC2s and that this contributes to generation of scratch behavior through activation of sensory neurons. First we found a close association of the peak of itch responses and cutaneous IL-31 expression. Second, we showed that IL-31 has short-term effects evoking itching, which is Stat3 independent, and long-term effects on increasing the sensitivity of sensory neurons. Third, we established that dermal cDC2s are critical cellular sources of IL-31 during wound repair and that day 5 dermal cDC2s are sufficient to evoke itch responses in naive mice. Finally we demonstrate that IL-31 expression in cDC2s requires Smad-dependent TGF- $\beta$  signaling. These findings provide the immunological and neurological underpinnings of the widely known sensation of itching that is experienced in the later stages of skin wound healing.

It is thought that many pruritogens evoke itching (Steinhoff et al., 2018; Trier and Kim, 2018), but the principle underlying the agents responsible for the itching induced during cutaneous repair have not been studied. Here we discovered that the cytokine IL-31, based on our unbiased RNA-seq analysis, qPCR, and protein analysis, was prominently expressed, peaking at approximately the same time when itching was most intense. In mice and humans, type 2 cytokine signaling contributes to itching (Oetjen et al., 2017), and IL-31 was initially described as a Th2 cytokine mainly related to dermatitis and some respiratory diseases (Bilsborough et al., 2010; Cevikbas et al., 2014; Dillon et al., 2004). Supporting this function of IL-31 in itching, anti-IL-31 receptor antibodies have been reported to relieve dermatitis in a mouse model and human patients (Kasutani et al., 2014; Ruzicka et al., 2017). Therefore, we propose that IL-31 is also a likely agent contributing to pruritus when the skin is recovering from injury, and a slow build-up of IL-31 causes the increasing prurceptive sensation that builds during wound healing during this process. For this reason, IL-31 might be a good target for treatment of pruritus in more extensive body surface areas, such as with burns.

We wondered why IL-31 might be elevated during wound healing and considered that it might influence immune cell functions at the repair site and, therefore, be important in wound closure or other processes producing an intact barrier. This idea was not borne out because, in *Il31<sup>-/-</sup>* mice, we did not find significant changes in wound healing. This still does not answer what

(F) Dermal cDC2 from normal skin treated with or without TGF- $\beta$ 1 for 24 h were injected (i.d., 15,000 cells per site) to the dorsal area of normal B6 mice, and scratching bouts on the dorsal area of dermal cDC2 recipients were counted 3 h after injection. Data were from 3 independent experiments, each circle represents one mouse (n = 6). Student's t test was used for comparison. Bars represent means  $\pm$  SEM. \*p < 0.05.

(G) Dermal cDC2 from normal or *Tgfb1*-deficient mice (tamoxifen-treated *Tgfb1<sup>fl/fl</sup> Ert2-Cre* mice) were also treated with TGF- $\beta$ 1 for 24 h and injected into the dorsal area of normal B6 mice, and scratch counts were determined in recipients of dermal cDC2s. Data were from 3 independent experiments. Each circle represents one mouse (n = 6). Student's t test was used for comparison. Bars represent means  $\pm$  SEM. \*p < 0.05.

See also Figure S6 for more details.

IL-31 might be doing, but it means that therapeutic agents neutralizing IL-31 would not impair wound recovery. Future experiments might investigate the reasons for elevated IL-31 during wound repair. In addition, studies have shown that IL-31 has roles in nerve growth (Feld et al., 2016) and neuropeptide release (Meng et al., 2018); it is reasonable that wound itching occurs when nerve fibers are remodeling into the dermis/epidermis.

IL-31 has been reported previously to acutely induce itching via activation of IL-31Ra on TRPV1<sup>+</sup> sensory neurons, which innervate the skin (Cevikbas et al., 2014), and to also evoke delayed itching (Arai et al., 2013; Hawro et al., 2014). Here we showed that, at least in part, IL-31 may increase sensory neuron activity by upregulation of expression of molecules involved in signaling reception (*Il31Ra*), signal transduction (*Trpv1*), and signal transmission (*Nppb*). These increases in expression are long-term effects and are Stat3 dependent. In turn, this suggests that Stat3 might be another potential therapeutic target for use in IL-31-dependent itching.

In the dermis, cDCs are conventional resident DCs and have critical roles in guarding the host against invading pathogens while limiting tissue damage. They are involved in some pathologies, including infectious and parasitic diseases transmitted through the skin (Clausen and Stoitzner, 2015; Valladeau and Saeland, 2005). cDCs are the most abundant type of DCs in the healthy mouse dermis (Malissen et al., 2014; Tamoutounour et al., 2013); upon migration to draining lymph nodes, they can trigger Th2 cell differentiation (Kitajima and Ziegler, 2013) and induce production of regulatory T cells (Guilliams et al., 2010). For these reasons, their numbers are substantially increased at sites of barrier disruption. It has been reported previously that nociceptive sensory neurons, by interacting with dermal cDCs, can regulate the IL-23/IL-17 pathway and control cutaneous immune responses in a model of psoriasis (Riol-Blanco et al., 2014). Here we focused on the reverse direction and investigated how immune cells affect the peripheral nervous system and behavior. Our results show that elevated amounts of IL-31 in wounds is predominantly generated by dermal cDC2s. Therefore, our results show that there is reciprocal signaling between cutaneous cDC2s and peripheral sensory neurons, highlighting the importance of the interaction between the immune and nervous systems in the skin.

TGF- $\beta$  signaling is crucial during wound healing; it has a broad spectrum effects on almost every cell type, including keratinocytes, fibroblasts, DCs, and monocytes (Ashcroft et al., 1999). TGF- $\beta$ 1 is important for wound closure by facilitating fibroblast contraction in the collagen matrix (Meckmongkol et al., 2007) and development of hypertrophic and keloid scars (Colwell et al., 2005) and for inducing and sustaining activation of keloid fibroblasts (Wang et al., 2007). TGF- $\beta$ 1 directs differentiation of monocytes into LCs and is crucial for the cutaneous contingent of migratory DCs (Felker et al., 2010). Moreover, TGF- $\beta$  may induce tolerogenic DCs, which can skew effector T cell immune response into cells of a predominantly anti-inflammatory Th2-like phenotype or may induce generation of regulatory T cells (Chen et al., 2003; Esebani and Langridge, 2017; van Duivenvoorde et al., 2006). In this study, we expand the list of TGF- $\beta$  functions to wound healing-induced itching by demonstrating that TGF- $\beta$  signaling increases IL-31 production in dermal cDC2s.

Here we provide evidence of an IL-31-mediated effect on the sensory nervous system and mammalian behavior. By identifying this neuro-immunologic pathway and determining key mechanistic steps involved in this process, we identify potential therapeutic targets for itching that occurs during wound healing and potentially other conditions that disrupt the skin barrier and cause itching.

### Limitations of Study

Although our study shows that IL-31 is responsible for itch responses during wound healing, it remains an exciting question whether there is any other biological function of IL-31 in that period. Future experiments might also investigate the reasons for elevated IL-31 during wound repair; it would be insightful to focus on the roles of IL-31 in nerve growth and neuropeptide release. Our study could be improved by some direct visual evidence of IL-31 expression in the skin, which we were unable to provide because of the coronavirus disease 2019 (COVID-19) pandemic.

### STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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### SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at <https://doi.org/10.1016/j.immuni.2020.06.023>.

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#### AUTHOR CONTRIBUTIONS

J.X. designed and performed experiments, analyzed data, and wrote the manuscript. P.Z., L.H., D.Z., N.L., W.J., and Y.H. designed and performed experiments. P.-Y.T. provided critical methods and analyzed RNA sequence data. F.W., O.L., N.G., J.Y., A.C., and S.W. provided critical scientific input. M.A.H. supervised the study and wrote the manuscript. W.C. conceived, initiated, and supervised the whole study; designed experiments; and wrote the manuscript.

#### DECLARATION OF INTERESTS

The authors declare no competing interests.

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#### REFERENCES

- Arai, I., Tsuji, M., Takeda, H., Akiyama, N., and Saito, S. (2013). A single dose of interleukin-31 (IL-31) causes continuous itch-associated scratching behaviour in mice. *Exp. Dermatol.* **22**, 669–671.
- Ashcroft, G.S., Yang, X., Glick, A.B., Weinstein, M., Letterio, J.L., Mizel, D.E., Anzano, M., Greenwell-Wild, T., Wahl, S.M., Deng, C., and Roberts, A.B. (1999). Mice lacking Smad3 show accelerated wound healing and an impaired local inflammatory response. *Nat. Cell Biol.* **1**, 260–266.
- Ashcroft, G.S., Lei, K., Jin, W., Longenecker, G., Kulkarni, A.B., Greenwell-Wild, T., Hale-Donze, H., McGrady, G., Song, X.Y., and Wahl, S.M. (2000). Secretory leukocyte protease inhibitor mediates non-redundant functions necessary for normal wound healing. *Nat. Med.* **6**, 1147–1153.
- Barrientos, S., Stojadinovic, O., Golinko, M.S., Brem, H., and Tomic-Canic, M. (2008). Growth factors and cytokines in wound healing. *Wound Repair Regen.* **16**, 585–601.
- Bautista, D.M., Wilson, S.R., and Hoon, M.A. (2014). Why we scratch an itch: the molecules, cells and circuits of itch. *Nat. Neurosci.* **17**, 175–182.
- Bilsborough, J., Mudri, S., Chadwick, E., Harder, B., and Dillon, S.R. (2010). IL-31 receptor (IL-31RA) knockout mice exhibit elevated responsiveness to oncostatin M. *J. Immunol.* **185**, 6023–6030.
- Braiman-Wiksman, L., Solomonik, I., Spira, R., and Tennenbaum, T. (2007). Novel insights into wound healing sequence of events. *Toxicol. Pathol.* **35**, 767–779.
- Cevikbas, F., Wang, X., Akiyama, T., Kempkes, C., Savinko, T., Antal, A., Kukova, G., Buhl, T., Ikoma, A., Buddenkotte, J., et al. (2014). A sensory neuron-expressed IL-31 receptor mediates T helper cell-dependent itch: Involvement of TRPV1 and TRPA1. *J. Allergy Clin. Immunol.* **133**, 448–460.
- Chavan, S.S., Pavlov, V.A., and Tracey, K.J. (2017). Mechanisms and Therapeutic Relevance of Neuro-immune Communication. *Immunity* **46**, 927–942.
- Chen, W., Jin, W., Hardegen, N., Lei, K.J., Li, L., Marinos, N., McGrady, G., and Wahl, S.M. (2003). Conversion of peripheral CD4+CD25- naive T cells to CD4+CD25+ regulatory T cells by TGF-beta induction of transcription factor Foxp3. *J. Exp. Med.* **198**, 1875–1886.
- Clausen, B.E., and Stoitzner, P. (2015). Functional Specialization of Skin Dendritic Cell Subsets in Regulating T Cell Responses. *Front. Immunol.* **6**, 534.
- Colwell, A.S., Phan, T.T., Kong, W., Longaker, M.T., and Lorenz, P.H. (2005). Hypertrophic scar fibroblasts have increased connective tissue growth factor expression after transforming growth factor-beta stimulation. *Plast. Reconstr. Surg.* **116**, 1387–1390, discussion 1391–1392.
- Cukjati, D., Rebersek, S., and Miklavcic, D. (2001). A reliable method of determining wound healing rate. *Med. Biol. Eng. Comput.* **39**, 263–271.
- Dillon, S.R., Sprecher, C., Hammond, A., Bilsborough, J., Rosenfeld-Franklin, M., Presnell, S.R., Haugen, H.S., Maurer, M., Harder, B., Johnston, J., et al. (2004). Interleukin 31, a cytokine produced by activated T cells, induces dermatitis in mice. *Nat. Immunol.* **5**, 752–760.
- Esebanmen, G.E., and Langridge, W.H.R. (2017). The role of TGF-beta signaling in dendritic cell tolerance. *Immunol. Res.* **65**, 987–994.
- Feld, M., Garcia, R., Buddenkotte, J., Katayama, S., Lewis, K., Muirhead, G., Hevezi, P., Plessner, K., Schrupf, H., Krjutskov, K., et al. (2016). The pruritus- and TH2-associated cytokine IL-31 promotes growth of sensory nerves. *J. Allergy Clin. Immunol.* **138**, 500–508.e24.
- Felker, P., Seré, K., Lin, Q., Becker, C., Hristov, M., Hieronymus, T., and Zenke, M. (2010). TGF-beta1 accelerates dendritic cell differentiation from common dendritic cell progenitors and directs subset specification toward conventional dendritic cells. *J. Immunol.* **185**, 5326–5335.
- Guilliams, M., Crozat, K., Henri, S., Tamoutounour, S., Grenot, P., Devilard, E., de Bovis, B., Alexopoulou, L., Dalod, M., and Malissen, B. (2010). Skin-draining lymph nodes contain dermis-derived CD103(-) dendritic cells that constitutively produce retinoic acid and induce Foxp3(+) regulatory T cells. *Blood* **115**, 1958–1968.
- Han, L., Ma, C., Liu, Q., Weng, H.J., Cui, Y., Tang, Z., Kim, Y., Nie, H., Qu, L., Patel, K.N., et al. (2013). A subpopulation of nociceptors specifically linked to itch. *Nat. Neurosci.* **16**, 174–182.
- Hawro, T., Saluja, R., Weller, K., Altrichter, S., Metz, M., and Maurer, M. (2014). Interleukin-31 does not induce immediate itch in atopic dermatitis patients and healthy controls after skin challenge. *Allergy* **69**, 113–117.
- Huang, J., Polgár, E., Solinski, H.J., Mishra, S.K., Tseng, P.Y., Iwagaki, N., Boyle, K.A., Dickie, A.C., Kriegbaum, M.C., Wildner, H., et al. (2018). Circuit dissection of the role of somatostatin in itch and pain. *Nat. Neurosci.* **21**, 707–716.
- Imamachi, N., Park, G.H., Lee, H., Anderson, D.J., Simon, M.I., Basbaum, A.I., and Han, S.K. (2009). TRPV1-expressing primary afferents generate behavioral responses to pruritogens via multiple mechanisms. *Proc. Natl. Acad. Sci. USA* **106**, 11330–11335.
- Jin, H., He, R., Oyoshi, M., and Geha, R.S. (2009). Animal models of atopic dermatitis. *J. Invest. Dermatol.* **129**, 31–40.
- Kashem, S.W., Haniffa, M., and Kaplan, D.H. (2017). Antigen-Presenting Cells in the Skin. *Annu. Rev. Immunol.* **35**, 469–499.
- Kasutani, K., Fujii, E., Ohyama, S., Adachi, H., Hasegawa, M., Kitamura, H., and Yamashita, N. (2014). Anti-IL-31 receptor antibody is shown to be a potential therapeutic option for treating itch and dermatitis in mice. *Br. J. Pharmacol.* **171**, 5049–5058.
- Keyes, B.E., Liu, S., Asare, A., Naik, S., Levorse, J., Polak, L., Lu, C.P., Nikolova, M., Pasolli, H.A., and Fuchs, E. (2016). Impaired Epidermal to Dendritic T Cell Signaling Slows Wound Repair in Aged Skin. *Cell* **167**, 1323–1338.e14.
- Kissenpfennig, A., Henri, S., Dubois, B., Laplace-Builhé, C., Perrin, P., Romani, N., Tripp, C.H., Douillard, P., Leserman, L., Kaiserlian, D., et al. (2005). Dynamics and function of Langerhans cells in vivo: dermal dendritic cells colonize lymph node areas distinct from slower migrating Langerhans cells. *Immunity* **22**, 643–654.
- Kitajima, M., and Ziegler, S.F. (2013). Cutting edge: identification of the thymic stromal lymphopoietin-responsive dendritic cell subset critical for initiation of type 2 contact hypersensitivity. *J. Immunol.* **191**, 4903–4907.
- Lyman, I.R., Tenery, J.H., and Basson, R.P. (1970). Correlation between decrease in bacterial load and rate of wound healing. *Surg. Gynecol. Obstet.* **130**, 616–621.
- Malissen, B., Tamoutounour, S., and Henri, S. (2014). The origins and functions of dendritic cells and macrophages in the skin. *Nat. Rev. Immunol.* **14**, 417–428.
- Massagué, J. (1999). Wounding Smad. *Nat. Cell Biol.* **1**, E117–E119.
- Mast, B.A., and Schultz, G.S. (1996). Interactions of cytokines, growth factors, and proteases in acute and chronic wounds. *Wound Repair Regen.* **4**, 411–420.

- Meckmongkol, T.T., Harmon, R., McKeown-Longo, P., and Van De Water, L. (2007). The fibronectin synergy site modulates TGF-beta-dependent fibroblast contraction. *Biochem. Biophys. Res. Commun.* **360**, 709–714.
- Meng, J., Moriyama, M., Feld, M., Buddenkotte, J., Buhl, T., Szollosi, A., Zhang, J., Miller, P., Ghetti, A., Fischer, M., et al. (2018). New mechanism underlying IL-31-induced atopic dermatitis. *J. Allergy Clin. Immunol.* **141**, 1677–1689.e8.
- Meredith, M.M., Liu, K., Darrasse-Jeze, G., Kamphorst, A.O., Schreiber, H.A., Guermontprez, P., Idoyaga, J., Cheong, C., Yao, K.H., Niec, R.E., and Nussenzweig, M.C. (2012). Expression of the zinc finger transcription factor zDC (Zbtb46, Btbd4) defines the classical dendritic cell lineage. *J. Exp. Med.* **209**, 1153–1165.
- Mishra, S.K., and Hoon, M.A. (2013). The cells and circuitry for itch responses in mice. *Science* **340**, 968–971.
- Mishra, S.K., Tisel, S.M., Orestes, P., Bhangoo, S.K., and Hoon, M.A. (2011). TRPV1-lineage neurons are required for thermal sensation. *EMBO J.* **30**, 582–593.
- Nattkemper, L.A., Tey, H.L., Valdes-Rodriguez, R., Lee, H., Mollanazar, N.K., Albornoz, C., Sanders, K.M., and Yosipovitch, G. (2018). The Genetics of Chronic Itch: Gene Expression in the Skin of Patients with Atopic Dermatitis and Psoriasis with Severe Itch. *J. Invest. Dermatol.* **138**, 1311–1317.
- Oetjen, L.K., Mack, M.R., Feng, J., Whelan, T.M., Niu, H., Guo, C.J., Chen, S., Trier, A.M., Xu, A.Z., Tripathi, S.V., et al. (2017). Sensory Neurons Co-opt Classical Immune Signaling Pathways to Mediate Chronic Itch. *Cell* **171**, 217–228.e13.
- Parnell, L.K., Nedelec, B., Rachelska, G., and LaSalle, L. (2012). Assessment of pruritus characteristics and impact on burn survivors. *J. Burn Care Res.* **33**, 407–418.
- Prasad, A., Thode, H.C., Jr., Sandoval, S., and Singer, A.J. (2019). The association of patient and burn characteristics with itching and pain severity. *Burns* **45**, 348–353.
- Riol-Blanco, L., Ordovas-Montanes, J., Perro, M., Naval, E., Thiriout, A., Alvarez, D., Paust, S., Wood, J.N., and von Andrian, U.H. (2014). Nociceptive sensory neurons drive interleukin-23-mediated psoriasisform skin inflammation. *Nature* **510**, 157–161.
- Ross, R., and Odland, G. (1968). Human wound repair. II. Inflammatory cells, epithelial-mesenchymal interrelations, and fibrogenesis. *J. Cell Biol.* **39**, 152–168.
- Ruzicka, T., Hanifin, J.M., Furue, M., Pulka, G., Mlynarczyk, I., Wollenberg, A., Galus, R., Etoh, T., Mihara, R., Yoshida, H., et al.; XCIMA Study Group (2017). Anti-Interleukin-31 Receptor A Antibody for Atopic Dermatitis. *N. Engl. J. Med.* **376**, 826–835.
- Schreiber, H.A., Loschko, J., Karssemeijer, R.A., Escolano, A., Meredith, M.M., Mucida, D., Guermontprez, P., and Nussenzweig, M.C. (2013). Intestinal monocytes and macrophages are required for T cell polarization in response to *Citrobacter rodentium*. *J. Exp. Med.* **210**, 2025–2039.
- Shim, W.S., Tak, M.H., Lee, M.H., Kim, M., Kim, M., Koo, J.Y., Lee, C.H., Kim, M., and Oh, U. (2007). TRPV1 mediates histamine-induced itching via the activation of phospholipase A2 and 12-lipoxygenase. *J. Neurosci.* **27**, 2331–2337.
- Shimada, S.G., and LaMotte, R.H. (2008). Behavioral differentiation between itch and pain in mouse. *Pain* **139**, 681–687.
- Solinski, H.J., Dranchak, P., Oliphant, E., Gu, X., Earnest, T.W., Braisted, J., Inglese, J., and Hoon, M.A. (2019a). Inhibition of natriuretic peptide receptor 1 reduces itch in mice. *Sci. Transl. Med.* **11**, eaav5464.
- Solinski, H.J., Kriegbaum, M.C., Tseng, P.Y., Earnest, T.W., Gu, X., Barik, A., Chesler, A.T., and Hoon, M.A. (2019b). Nppb Neurons Are Sensors of Mast Cell-Induced Itch. *Cell Rep.* **26**, 3561–3573.e4.
- Steinhoff, M., Buddenkotte, J., and Lerner, E.A. (2018). Role of mast cells and basophils in pruritus. *Immunol. Rev.* **282**, 248–264.
- Steward-Sharp, S.M., Laurence, A., Kanno, Y., Kotlyar, A., Villarino, A.V., Sciume, G., Kuchen, S., Resch, W., Wohlfert, E.A., Jiang, K., et al. (2014). A mouse model of HIES reveals pro- and anti-inflammatory functions of STAT3. *Blood* **123**, 2978–2987.
- Takamori, A., Nambu, A., Sato, K., Yamaguchi, S., Matsuda, K., Numata, T., Sugawara, T., Yoshizaki, T., Arae, K., Morita, H., et al. (2018). IL-31 is crucial for induction of pruritus, but not inflammation, in contact hypersensitivity. *Sci. Rep.* **8**, 6639.
- Tamoutounour, S., Guilliams, M., Montanana Sanchis, F., Liu, H., Terhorst, D., Malosse, C., Pollet, E., Ardouin, L., Luche, H., Sanchez, C., et al. (2013). Origins and functional specialization of macrophages and of conventional and monocyte-derived dendritic cells in mouse skin. *Immunity* **39**, 925–938.
- Tian, L., Rauvala, H., and Gahmberg, C.G. (2009). Neuronal regulation of immune responses in the central nervous system. *Trends Immunol.* **30**, 91–99.
- Trier, A.M., and Kim, B.S. (2018). Cytokine modulation of atopic itch. *Curr. Opin. Immunol.* **54**, 7–12.
- Tu, E., Chia, C.P.Z., Chen, W., Zhang, Y.E., Sun, L., and Chen, W. (2018). T Cell Receptor-Regulated TGF-beta Type I Receptor Expression Determines T Cell Quiescence and Activation. *Immunity* **48**, 745–759.e6.
- Valladeau, J., and Saeland, S. (2005). Cutaneous dendritic cells. *Semin. Immunol.* **17**, 273–283.
- van Duivenvoorde, L.M., van Mierlo, G.J., Boonman, Z.F., and Toes, R.E. (2006). Dendritic cells: vehicles for tolerance induction and prevention of auto-immune diseases. *Immunobiology* **211**, 627–632.
- Wang, Z., Gao, Z., Shi, Y., Sun, Y., Lin, Z., Jiang, H., Hou, T., Wang, Q., Yuan, X., Zhu, X., et al. (2007). Inhibition of Smad3 expression decreases collagen synthesis in keloid disease fibroblasts. *J. Plast. Reconstr. Aesthet. Surg.* **60**, 1193–1199.
- Yang, X., Letterio, J.J., Lechleider, R.J., Chen, L., Hayman, R., Gu, H., Roberts, A.B., and Deng, C. (1999). Targeted disruption of SMAD3 results in impaired mucosal immunity and diminished T cell responsiveness to TGF-beta. *EMBO J.* **18**, 2180–2191.
- Zhang, Q., Putheti, P., Zhou, Q., Liu, Q., and Gao, W. (2008). Structures and biological functions of IL-31 and IL-31 receptors. *Cytokine Growth Factor Rev.* **19**, 347–356.

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
<b>Antibodies</b>		
Anti-mouse CD45 Alexa Fluor 700 (30-F11)	eBioscience	Cat# 56-0451-82; RRID:AB_891454
Anti-mouse CD3 PerCP-eFluor 710 (17A2)	eBioscience	Cat# 46-0032-82; RRID:AB_1834427
Anti-mouse CD3 APC-eFluor 780 (17A2)	eBioscience	Cat# 47-0032-82; RRID:AB_1272181
Anti-mouse CD11c PerCP/Cy5.5 (N418)	BioLegend	Cat# 117328; RRID:AB_2129641
Anti-mouse CD11c FITC (N418)	eBioscience	Cat# 11-0114-82; RRID:AB_464940
Anti-mouse CD11b APC (M1/70)	eBioscience	Cat# 17-0112-82; RRID:AB_469343
Anti-mouse CD11b eFluor 450 (M1/70)	eBioscience	Cat# 48-0112-82; RRID:AB_1582236
Anti-mouse CD326 APC (G8.8)	eBioscience	Cat# 17-5791-82; RRID:AB_2716944
Anti-mouse CD326 APC-eFluor 780 (G8.8)	eBioscience	Cat# 47-5791-82; RRID:AB_2573986
Anti-mouse CD64 PE-Cy7 (X54-5/7.1)	BioLegend	Cat# 139313; RRID:AB_2563903
Anti-mouse CD64 APC (X54-5/7.1)	eBioscience	Cat# 17-0641-82; RRID:AB_2735010
Anti-mouse CD64 PerCP-eFluor 710 (X54-5/7.1)	eBioscience	Cat# 46-0641-82; RRID:AB_2735016
Anti-mouse F4/80 APC (BM8)	eBioscience	Cat# 17-4801-82; RRID:AB_2784648
Anti-mouse F4/80 PE-eFluor 610 (BM8)	eBioscience	Cat# 61-4801-82; RRID:AB_2574612
Anti-mouse MHC class II (I-A/I-E) PE (M5/114.15.2)	eBioscience	Cat# 12-5321-82; RRID:AB_465928
Anti-mouse MHC class II (I-A/I-E) eFluor 450 (M5/114.15.2)	eBioscience	Cat# 48-5321-82; RRID:AB_1272204
Anti-mouse CD103 PE (2E7)	eBioscience	Cat# 12-1031-82; RRID:AB_465799
Anti-mouse CD207 PE (eBioL31)	eBioscience	Cat# 12-2075-82; RRID:AB_763452
Anti-mouse CD117 (2B8)	eBioscience	Cat# 48-1171-82; RRID:AB_2574037
Anti-mouse FcεR1 alpha PerCP-eFluor 710 (MAR-1)	eBioscience	Cat# 46-5898-82; RRID:AB_2573801
Anti-mouse Stat1	Cell Signaling	Cat# 9172; RRID:AB_2198300
Anti-mouse pStat1	Cell Signaling	Cat# 9171S; RRID:AB_331591
Anti-mouse Stat3	Cell Signaling	Cat# 9139; RRID:AB_331757
Anti-mouse Stat3	Cell Signaling	Cat# 4904S; RRID:AB_331269
Anti-mouse pStat3	Cell Signaling	Cat# 9131S; RRID:AB_331586
Anti-mouse pStat3	Cell Signaling	Cat# 9145S; RRID:AB_2491009
Anti-mouse Stat5	Cell Signaling	Cat# 9363; RRID:AB_2196923
Anti-mouse pStat5	Cell Signaling	Cat# 9351S; RRID:AB_2315225
Anti-mouse Gapdh	Cell Signaling	Cat# 5014S; RRID:AB_10693448
Anti-mouse IL-31	ABcam	Cat# ab102750; RRID:AB_10710722
TGF-β1 Elisa kit	Promega	Cat# G7591; RRID:AB_2858628
IL-31 Elisa kit	eBioscience	Cat# BMS6030; RRID:AB_2575653
<b>Chemicals, Peptides, and Recombinant Proteins</b>		
Recombinant mouse IL-1β	R&D System	Cat# 401-ML
Recombinant mouse IL-6	R&D System	Cat# 206-IL
Recombinant mouse IL-17a	R&D System	Cat# 421-ML
Recombinant mouse IL-31	R&D System	Cat# 3028-ML
Recombinant human TGF- β1	R&D System	Cat# 240-B
Recombinant mouse TNF-α	R&D System	Cat# 410-MT
SB431542	Selleckchem	Cat# S1067
S31-201	Sigma	Cat# SML0330
SIS3	Sigma	Cat# S0447
Capsaicin	Sigma	Cat# M2028

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REAGENT or RESOURCE	SOURCE	IDENTIFIER
poly-D-lysine	Sigma	Cat# A-003-M
Tamoxifen	Sigma	Cat# T5648
Liberase DH	Sigma	Cat# LIBDH-RO
Papain	Worthington	Cat# LS003127
Collagenase type II	Worthington	Cat# LS004177
Dispase type II	Worthington	Cat# LS02104
Fluo-4	Thermo Fisher Scientific	Cat# F14201
Pluronic F-127	Thermo Fisher Scientific	Cat# P3000MP
JS-11	<a href="#">Solinski et al., 2019a</a>	N/A
<b>Critical Commercial Assays</b>		
RNeasy Mini Kit	QIAGEN	Cat# 74106
RNeasy Micro Kit	QIAGEN	Cat# 74004
High-Capacity cDNA Reverse Transcription Kit	Applied Biosystems	Cat# 4368814
TaqMan Gene Expression Master Mix	Applied Biosystems	Cat# 4369016
TaqMan PreAmp Master Mix Kit	Applied Biosystems	Cat# 4488593
<b>Deposited Data</b>		
Murine cutaneous wounds tissue RNA sequence data	This Paper	GEO accession GSE128193 <a href="https://www.ncbi.nlm.nih.gov/geo/query/acc.cgi?acc=GSE128193">https://www.ncbi.nlm.nih.gov/geo/query/acc.cgi?acc=GSE128193</a>
<b>Biological information</b>		
Pruritus self-assessments of patients who were scheduled for minor skin superficial surgery were recorded before and every other day after surgery for 7 days, no human tissue sample was taken for this study	This Paper	N/A
<b>Experimental Models: Organisms/Strains</b>		
Mouse: C57BL/6	The Jackson Laboratory	Cat# 000664
Mouse: <i>Il31</i> <sup>-/-</sup>	<a href="#">Takamori et al., 2018</a>	N/A
Mouse: <i>Trpv1</i> -cre	The Jackson Laboratory	Cat# 017769
Mouse: Rosa26 <sup>tdTomato</sup>	The Jackson Laboratory	Cat# 007914
Mouse: <i>Trpv1</i> -tdTomato	This paper	N/A
Mouse: mut- <i>Stat3</i>	The Jackson Laboratory	Cat# 027952
Mouse: zDC <sup>DTR</sup>	The Jackson Laboratory	Cat# 019506
Mouse: <i>Rag1</i> <sup>-/-</sup>	The Jackson Laboratory	Cat# 002216
Mouse: <i>Lang</i> <sup>DTR</sup>	The Jackson Laboratory	Cat# 016940
Mouse: <i>Csf1</i> <sup>DTR</sup>	The Jackson Laboratory	Cat# 024046
Mouse: <i>Csf1</i> <sup>DTR</sup> Lyz2-cre	<a href="#">Schreiber et al., 2013</a>	N/A
Mouse: <i>Tgfb1</i> <sup>fl/fl</sup> Ert2-cre	<a href="#">Tu et al., 2018</a>	N/A
Mouse: <i>Smad3</i> <sup>-/-</sup>	<a href="#">Yang et al., 1999</a>	N/A
Mouse: <i>Tgfb1</i> <sup>fl/fl</sup> Cd11c-cre	This paper	N/A
Mouse: <i>Tgfb1</i> <sup>fl/fl</sup> Lyz2-cre	This paper	N/A
<b>Oligonucleotides</b>		
TaqMan <i>Hprt</i> primer, Mm00446968_m1	Applied Biosystems	N/A
TaqMan <i>Gapdh</i> primer, Mm99999915_g1	Applied Biosystems	N/A
TaqMan <i>Il31</i> primer, Mm01194496_m1	Applied Biosystems	N/A
TaqMan <i>Il31ra</i> primer, Mm01304494_m1	Applied Biosystems	N/A
TaqMan <i>Trpa1</i> primer, Mm01227437_m1	Applied Biosystems	N/A
TaqMan <i>Trpv1</i> primer, Mm01246302_m1	Applied Biosystems	N/A
TaqMan <i>Nppb</i> primer, Mm01255770_g1	Applied Biosystems	N/A

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REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and Algorithms		
FlowJo 9 software	FlowJo	<a href="https://www.flowjo.com">https://www.flowjo.com</a> ; RRID:SCR_008520
GraphPad Prism 7 software	GraphPad Software	<a href="https://www.graphpad.com">https://www.graphpad.com</a> ; RRID:SCR_002798
RStudio	RStudio	<a href="https://rstudio.com/">https://rstudio.com/</a> ; RRID:SCR_000432
Other		
BD LSRFortessa	BD Biosciences	N/A
BD FACSAria cell sorter	BD Biosciences	N/A

**RESOURCE AVAILABILITY****Lead Contact**

Further information and requests for resources and reagents should be directed to and will be fulfilled by the Lead Contact, WanJun Chen ([wchen@mail.nih.gov](mailto:wchen@mail.nih.gov)).

**Materials Availability**

This study did not generate new unique reagents

**Data and Code Availability**

Murine cutaneous wounds tissue RNA sequence data in this paper were deposited in GEO accession (GSE128193; <https://www.ncbi.nlm.nih.gov/geo/query/acc.cgi?acc=GSE128193>)

**EXPERIMENTAL MODELS AND SUBJECT DETAILS****Human data of pruritus questionnaires**

The questionnaires for pruritus self-assessment was approved by the Institutional Ethics Committee of Beijing Stomatological Hospital affiliated to Capital Medical University; informed consent was obtained from all participants. Pruritus self-assessments were recorded for subjects who were scheduled for minor skin superficial surgery (please see [Method Details](#) for details). 12 subjects were enrolled finally (3 women and 9 men, mean age  $\pm$  SD: 53.3  $\pm$  12.6 years). Pruritus intensity was assessed using a 10-cm visual analog scale (VAS). Subjects were asked to evaluate and record the pruritus intensity before and every other day after surgery within 7 days. No human tissue sample was taken for this study.

**Mice**

C57BL/6, *Rag1*<sup>-/-</sup> mice, *Trpv1*-Cre mice, *Rosa26*<sup>tdTomato</sup> mice, *mut-Stat3* mice ([Steward-Tharp et al., 2014](#)), *zDC*<sup>DTR</sup> mice ([Meredith et al., 2012](#)), *Csf1r*<sup>DTR</sup> mice, *Lang*<sup>DTR</sup> mice ([Kissenpennig et al., 2005](#)) were obtained from The Jackson Laboratory. *Il31*<sup>-/-</sup> mice ([Takamori et al., 2018](#)) were obtained from Dr. Nakae's Lab. *Tgfb1*<sup>fl/fl</sup>*Ert2*-Cre, *Smad3*<sup>-/-</sup> (on a C57BL/6 background) were previously described and bred in our facility under specific pathogen-free conditions. *Trpv1*<sup>tdTomato</sup> mice were generated in-house by crossing *Trpv1*-Cre mice with *Rosa26*<sup>tdTomato</sup> mice. *Csf1r*<sup>DTR</sup> *Lyz2*-Cre mice (MM<sup>DTR</sup> mice) ([Schreiber et al., 2013](#)) were generated in-house by crossing *Lyz2*-Cre mice with *Csf1r*<sup>DTR</sup> mice. *Tgfb1*<sup>fl/fl</sup> *Cd11c*-Cre<sup>+</sup> mice were generated in-house by crossing *Cd11c*-Cre mice with *Tgfb1*<sup>fl/fl</sup> mice. *Tgfb1*<sup>fl/fl</sup> *Lyz2*-Cre<sup>+</sup> were generated in-house by crossing *Lyz2*-Cre mice with *Tgfb1*<sup>fl/fl</sup> mice. *Tgfb1*<sup>fl/fl</sup> *Ert2*-Cre mice were treated with tamoxifen (1  $\mu$ g/mouse) per day for 5 days to delete T $\beta$ RI. All mice used for experiments were aged 6-12 weeks, both male and female. All animal studies were performed according to National Institutes of Health (NIH) guidelines for use and care of live animals and approved by the Animal Care and Use Committees of National Institute of Dental and Craniofacial Research (NIDCR).

**METHOD DETAILS****Enroll and exclusion criteria for human pruritus questionnaires**

All subjects must fulfill all the following items: (1) a superficial surgery is necessary for the subject diagnosed with a superficial cyst or benign tumor; (2) the expected wound will be 1 cm to 3 cm long; (3) the subject has no active systemic disease for 1 year and have a negative history of skin diseases; (4) the surgical area has no inflammation within the recent 6 months and have no sign of infection; (5) subject must be informed of the investigational nature of this study and given written informed consent. Exclusion criteria: (1) Active, uncontrolled infections in surgical area or systemically; (2) pathology report shows as a malignant tumor or Kimura's disease; (3) failed to follow up entirely.

### Bone marrow chimeras and diphtheria toxin injection

C57BL/6 hosts were irradiated with 12Gy split into 3 doses and reconstituted by tail vein injection of  $5 \times 10^6$  bone marrow cells from WT, *Il31<sup>-/-</sup>* or zDC<sup>DTR</sup> donors. Mice were allowed to reconstitute for 6 weeks prior to use. Diphtheria toxin (DT) was purchased from Sigma-Aldrich. zDC<sup>DTR</sup> bone marrow chimeras were injected *i.p.* with 20 ng DT per gram of body weight (500 ng/mouse) on the first day of DC depletion and with 4 ng DT per gram body weight (100 ng/mouse) on all subsequent days. C57BL/6, Lang<sup>DTR</sup>, and MM<sup>DTR</sup> mice received 4 ng DT per gram body weight (100 ng/mouse) at any time. Since we found that macrophage depletion at the beginning of incising would delay the wound healing or even fatal for mice, DT was injected (*i.p.*, 100ng/mouse) to MM<sup>DTR</sup> mice on the 3<sup>rd</sup> of wound healing and every day thereafter.

### Murine wound healing

Mice were anesthetized, dorsum shaved, cleaned with alcohol, and 2 equidistant 1cm full-thickness incisional wounds were made through the skin and left to heal. Wounds tissue (0.5 cm around incision) and dorsal root ganglion (DRG) that innervate the wound were harvested at indicated days and bisected for histology, snap-frozen in for RNA analysis/protein extraction, or DMEM contained 10% fetal bovine serum on ice for flow cytometry. Wound sizes were measured and wound healing rates were evaluated by the formula  $((\pi/4) \times length_0 \times width_0 - (\pi/4) \times length_f \times width_f) / (day_f - day_0) \times (\pi/4) \times length_0 \times width_0 \times 100$  (Cukjati et al., 2001; Lyman et al., 1970) and HE staining (Braiman-Wiksman et al., 2007).

### IL-31 intradermal injection

For wound healing model, we intradermally injected IL-31 30 ng/site (by this dose IL-31 could not induce itch in naive mice 8 hours later; Arai et al., 2013) into wounds every 12 hours for 3 times from the fourth day after wounds were cut, and the behavior recordings were taken 8 hours after the last injection. For mut-*Stat3* mice or wild-type control mice, we injected IL-31 1  $\mu$ g/site on the dorsal area intradermally, and observe the itching behaviors 1 hour later; 8 hours after the 1<sup>st</sup> injection, another IL-31 injection (1  $\mu$ g/site, *i.d.*) on the same spot, itching behaviors were recorded again 1 hour after the 2<sup>nd</sup> injection.

### Pruriceptive behavior measurement

To measure the pruriceptive behaviors, mice were placed in clear plastic enclosures with an optical cannula, which could rotate to allow free movement of the mouse. Itch behavioral responses were videotaped during the experiment. The behavior experiments and analysis were done blinded. Scratch (by the hind leg) bouts around the wounds or dendritic cells injected area were counted for 30 or 60 minutes.

### RNA-seq analysis

Two wounds tissue from one animal were pooled, three animals were used per time point. The skin was cleaned of muscle and fat tissue; total RNA was extracted using the RNeasy mini kits (QIAGEN), purified using Direct-zol RNA MiniPrep kit (Zymo Research). Next-generation libraries were prepared using the VAHTS TM mRNA-seq V2 Library Prep Kit for Illumina (Vazyme, #NR601). RNA-seq libraries were run on an Illumina HiSeq X-Ten next-generation sequencer. Analysis of RNA-seq data was done using the DESeq package in R.

### Cell culture of dorsal root ganglion neurons

Dorsal root ganglion (DRG) neurons were primarily cultured, as described previously. Briefly, thoracic and lumbar DRGs were dissected and collected from adult mice and transferred into HBSS without  $Ca^{2+}/Mg^{2+}$  on ice. F12 with 10% FCS and 100 U/ml penicillin/streptomycin was used as a culture medium. Ganglia were incubated with 1.5 mL papain (40 U/ml, Worthington) for 10 min at 37°C and then with 3 mL collagenase type II (4 mg/ml, Worthington)/ dispase type II (4.67 mg/ml, Worthington) combined solution for 10 min at 37°C. Dissociated cells were plated on poly-D-lysine-treated small coverslips and incubated for 2 to 3 days at 37°C in 95% air/5% CO<sub>2</sub>.

### Calcium image

DRG neurons were stained by 5  $\mu$ M Fluo-4 (Thermo Fisher Scientific) with 0.02% F-127 (Thermo Fisher Scientific) in HBSS<sup>+/+</sup> RP free buffer at 37°C for 30 mins. Then coverslips with cells were washed, moved to a custom-built chamber, and incubated with image medium (pH 7.4; 140 mM NaCl, 5 mM KCl, 2 mM CaCl<sub>2</sub>, 2 mM MgCl<sub>2</sub>, 10 mM HEPES, 10 mM Glucose). Calcium imaging experiments were performed under a Nikon confocal microscope with 488 nm excitation wavelength. Neurons were stimulated by Capsaicin (50 nM, Sigma) 10 s after the time lapse started. Images were analyzed offline with an NIH ImageJ software, data were normalized by using the initial image as basal fluorescence, and presented as the relative change in fluorescence ( $\Delta F/F_0$ ), where  $F_0$  is basal fluorescence and  $\Delta F = F - F_0$

### Flow cytometry

The skin was cleaned of fat tissue and cut into small pieces, incubated in Liberase DH (0.5 mg/ml, Sigma) for 90 min before finally shredding through 70- $\mu$ m cell strainers (BD PharMingen). After isolation, cell suspensions were washed by 0.5% BSA in PBS and

passed through 40  $\mu\text{m}$  cell strainers (BD PharMingen), and cell populations were characterized by flow cytometry. Stained cells were analyzed on LSRFortessa (BD Biosciences) or separated by FACSAria cell sorter (BD Biosciences). Data were analyzed with FlowJo software,

### Dermal conventional type 2 dendritic cells culture and injection

Dermal conventional type 2 dendritic cells (cDC2) were sorted by FACS Aria cell sorter (Zombie<sup>-</sup>CD45<sup>+</sup>CD3<sup>-</sup>CD64<sup>-</sup>CD11c<sup>+</sup>CD326<sup>-</sup>CD11b<sup>+</sup>MHC II<sup>+</sup>) and cultured with complete medium (RPMI 1640 supplemented with 10% FBS, L-glutamine, penicillin/streptomycin, 2-mercaptoethanol) contained GM-CSF (20 ng/ml, Peprotech). For cDC2 injection, mice were dorsum shaved 1 day before injection, cDC2 were washed and suspended in HBSS<sup>+/+</sup> RP free buffer and injected intradermally (5000 cells or 15000 cells in 20  $\mu\text{L}$  per site), pruriceptive behaviors were observed before and after injections.

### Real-time PCR

Total RNA was derived from cultured cells with RNeasy Mini kits (QIAGEN) or RNeasy Micro kits (QIAGEN), cDNA was synthesized using a High Capacity cDNA Reverse Transcription kit (Applied Biosystems). For sorted cells, a TaqMan PreAmp Master Mix Kit (Applied Biosystems) was used before quantitative real-time PCR. Quantitative real-time PCR was performed according to the protocol of TaqMan gene expression assay kits (Applied Biosystems). Results from leukocytes were normalized to the expression of *Hprt* mRNA, results from tissue were normalized to the expression of *Gapdh* mRNA.

### Antibodies and reagents

The following fluorochrome-conjugated antibodies were used for flow cytometry surface staining: anti-mouse CD45 (30-F11, eBioscience), anti-mouse CD3 (17A3, eBioscience), anti-mouse CD11c (N418, eBioscience), anti-mouse CD11b (M1/70, eBioscience), anti-mouse MHC class II (I-A/I-E) (M5/114.15.2, eBioscience), anti-mouse F4/80 (BM8, eBioscience), anti-mouse CD64 (X54-5/7.1, eBioscience), anti-mouse CD117 (2B8, eBioscience), anti-mouse Fc epsilon Receptor 1 alpha (MAR-1, eBioscience), anti-mouse CD207 (eBioL31, eBioscience), anti-mouse CD326 (G8.8, eBioscience), anti-mouse CD103 (2E7, eBioscience). Dead cells were excluded from analysis using Zombie Yellow Fixable Viability Kit (Biolegend). Recombined proteins and chemicals: IL-1 $\beta$  (401-ML, R&D System), IL-6 (206-IL, R&D System), IL-17a (421-ML, R&D System), IL-31 (3028-ML, R&D System), TGF- $\beta$ 1 (240-B, R&D System), TNF- $\alpha$  (410-MT, R&D System), SB431542 (ALK5 inhibitor, Selleckchem), S3I-201 (Stat3 inhibitor, Selleckchem), and SIS3 (Smad3 inhibitor, Sigma) were used in cell culturing for different conditions. Anti-mouse Stat1 (#9172, Cell Signaling), anti-mouse pStat1 (#9171S, Cell Signaling), anti-mouse Stat3 (#9139, Cell Signaling), anti-mouse pStat3 (#9131S, Cell Signaling), anti-mouse Stat5 (#9363, Cell Signaling), anti-mouse pStat5 (#9351S, Cell Signaling), anti-mouse Gapdh (#5014S, Cell Signaling), anti-mouse IL-31 (ab102750, Abcam) were used for western blot. TGF $\beta$ 1 Elisa kit (G7591, Promega) and IL-31 Elisa kit (BMS6030, eBioscience) were used for TGF $\beta$ 1 or IL-31 protein determination.

### Statistical analysis

Statistical analysis was performed using either unpaired two-tailed Student's t tests or one-way ANOVA in GraphPad Prism.