Patterning the embryonic pulmonary mesenchyme

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Abbreviations: DC, diffusion component; Fgf, fibroblast growth factor; Foxp1, Forkhead Box P1; Gli1, glioma-associated oncogene 1; Hoxb6, homeobox B6; Lef1, Lymphoid Enhancer Binding Factor 1; MGI, Mouse Genome Informatics; Myocd, myocardin; Shh, sonic hedgehog, SMA, smooth muscle actin; SRF, serum response factor; TGF, transforming growth factor; TTF-1, thyroid transcription factor 1; UMAP, uniform manifold approximation and projection; Wnt, wingless-Type MMTV Integration Site Family; WT1, Wilms tumor 1

Abstract

Smooth muscle guides morphogenesis of epithelia during development of several organs, including the mammalian lung. However, it remains unclear how airway smooth-muscle differentiation is spatiotemporally patterned and whether it originates from distinct mesenchymal progenitors. Using single-cell RNA-sequencing of embryonic mouse lungs, we show that the pulmonary mesenchyme contains a continuum of cell identities, but no distinct progenitors. Transcriptional variability correlates with sub-epithelial and sub-mesothelial mesenchymal compartments that are regulated by Wnt signaling. Live-imaging and tension sensors reveal patterned migratory behaviors and cortical forces in each compartment, and show that sub-epithelial mesenchyme gives rise to airway smooth muscle. Differentiation trajectory reconstruction reveals that cytoskeleton, adhesion, and Wnt signaling pathways are activated early in differentiation. Finally, we show that Wnt activation stimulates the earliest stages of differentiation and induces local accumulation of mesenchymal F-actin, which influences epithelial morphology. Our work provides the first single-cell view of pulmonary mesenchymal patterning during branching morphogenesis.

Introduction

Smooth muscle and similar contractile cell types influence the morphogenesis of epithelial tissues[1-3]. Branching of the mammalian airway epithelium has long been thought to involve smooth-muscle differentiation from the surrounding pulmonary mesenchyme[4-8]. Accordingly, ex vivo culture revealed that patterned airway smooth-muscle differentiation specifies cleft sites to promote epithelial bifurcation and shapes the domain branches that establish the underlying architecture of the murine lung[9,10]. It is therefore surprising that the smooth-muscle transcription factor myocardin (*Myocd*) is dispensable for lung branching morphogenesis[11] and that mice lacking α-smooth muscle actin (αSMA or *Acta2*) are viable and only develop deleterious phenotypes in smooth muscle and similar tissues under conditions of high mechanical stress[12,13]. These studies reveal the complexity (and robustness) of smooth-muscle differentiation and transcriptional identity during development and highlight the importance of uncovering the factors that define a smooth-muscle cell and control its differentiation.

Lung development is intricately regulated by signaling between the epithelium, mesothelium, and mesenchyme. Shh signaling from the epithelium is required for airway smooth-muscle differentiation[14], while Fgf9 signaling from the mesothelium prevents differentiation[15]. The physical layout of the tissue and the differing diffusible signals from the epithelium and mesothelium could potentially establish separate mesenchymal compartments. In particular, it appears that epithelial and mesothelial signals directly influence the behavior of the sub-epithelial and sub-mesothelial mesenchyme, respectively[16,17].

Cells from different locations within the pulmonary mesenchyme possess different capacities for differentiation: mesenchyme that is transplanted from stalk to tip regions fails to migrate towards the epithelium or differentiate into smooth muscle unless it is exposed to Wnt1[18]. Wnt signaling may therefore be involved in a compartment-specific manner in specifying smooth-muscle progenitor identity and behavior. Consistently, *Wnt2a* is expressed in the distal mesenchyme[19] and the expression of the *Axin2* is strongest in the mesenchyme around branch tips[20]. Deleting *Ctnnb1* (β-catenin) from the mesenchyme delays branching morphogenesis and inhibits mesenchymal growth and survival[17,21,22]. Expressing stabilized β-catenin leads to disorganized smooth-muscle wrapping[18], and Wnt2 promotes the expression of myogenic transcription factors to support robust smooth muscle differentiation[23].

Lineage-tracing studies based on single marker genes have not identified a distinct airway smooth-muscle progenitor[24,25]. Additionally, the signals required for patterned smooth-muscle differentiation remain unclear. Multiple pathways have been implicated but studying each one individually will not reveal how they interact to achieve spatiotemporal control. To circumvent these problems, we used single-cell RNA-sequencing (scRNA-seq) analysis. Since smooth muscle differentiates continuously during lung branching morphogenesis[3], scRNA-seq analysis at a single snapshot in time can be used to interrogate cell identities ranging from undifferentiated progenitor to mature smooth muscle[26,27].

ScRNA-seq analysis of *E*11.5 mouse lungs revealed a continuum of mesenchymal and smooth-muscle cell identities, but no distinct smooth-muscle progenitor population. Instead,

mesenchymal cell heterogeneity reflects spatially distinct, Wnt-dependent sub-epithelial and sub-mesothelial compartments. Live-imaging and tension-sensor experiments revealed differences in motility and cortical tension between compartments, and showed that airway smooth-muscle cells arise from the sub-epithelial mesenchyme. Computationally reconstructing this differentiation trajectory showed that cytoskeletal, adhesion, and Wnt signaling genes are upregulated early during differentiation, and that the airway smooth-muscle gene-expression program is largely *Myocd*-independent. Our computational analyses uncovered a role for Yap1 in mesenchymal patterning and showed that differentiating cells systematically downregulate genes involved in proliferative metabolism. Finally, we found that activated Wnt signaling causes an enrichment of nascent smooth-muscle cells and F-actin in the mesenchyme and prevents epithelial branching. Overall, we provide the first single-cell view of airway smooth-muscle differentiation and demonstrate that the earliest steps of differentiation involve Wnt-dependent mesenchymal stiffening that shapes epithelial branches.

Results

scRNA-seq analysis reveals expected populations of cells in the embryonic murine lung

We carried out scRNA-seq using cells isolated from the left lobes of lungs of CD1 mouse embryos harvested at *E*11.5 and analysed the data with Seurat[28] (**Fig. 1a**, **Supplementary Fig. 1a-g**). After removing contaminating cells and correcting for cell-cycle stage (**Supplementary Fig. 1h-k**), clustering identified 6 populations of cells, each containing cells from both replicates (**Fig. 1b-c**).We identified mesenchymal clusters expressing homeobox B6 (*Hoxb6*) and pleiotrophin (*Ptn*), a smooth-muscle cluster expressing *Acta2*, an epithelial cluster expressing

thyroid transcription factor 1 (TTF-1 or *Nkx2.1*), a vascular-endothelial cluster expressing VE-cadherin (*Cdh5*), and a mesothelial cluster expressing Wt1 (**Fig. 1b-e, Supplementary Table 1**).

We then isolated and reclustered the closely-related mesenchymal and smooth-muscle populations, and found that the *Hoxb6*-, *Ptn*-, and *Acta2*-expressing cells still clustered together in a similar pattern (**Supplementary Fig. 2a-b**). Previous studies used lineage-tracing of Axin2-, Fgf10-, Gli1-, and Wt1-expressing cells in an attempt to identify smooth-muscle progenitors[24,25]. However, none of these markers labeled a distinct population in our dataset (**Supplementary Fig. 2d-g**). Further analysis of reclustered mesenchymal cells provided no additional evidence for a distinct smooth-muscle progenitor (**Supplementary Fig. 2h-q**). Similar to other developing tissues[29,30], the embryonic pulmonary mesenchyme does not harbor a distinct progenitor population, but contains of a continuum of cell states.

Undifferentiated mesenchymal-cell clusters represent spatially distinct populations

To gain insight into mesenchymal patterning, we examined the expression of markers that distinguished clusters 0 and 1 (**Supplementary Table 2**). Immunofluorescence analysis of *E*11.5 lungs showed that Lef1^{+} cells are present adjacent to the epithelium, suggesting that these sub-epithelial cells may represent cluster 0 (**Fig. 2a**). Conversely, Foxp1^{+} cells are mostly in sub-mesothelial regions and in the medial mesenchyme, suggesting that these cells comprise cluster 1 (**Fig. 2b**). Apart from their differential expression patterns in the mesenchyme, Lef1 and Foxp1 are detected in airway smooth muscle (**Fig 2c, Supplementary Fig. 3a-b**), and Foxp1 is detected in the epithelium and mesothelium (**Fig 2b-c**). These data suggest that the computationally

identified mesenchymal clusters represent spatially distinct populations within the embryonic pulmonary mesenchyme. Therefore, we delineated two mesenchymal compartments, hereafter referred to as sub-epithelial (cluster 0) and sub-mesothelial (cluster 1), following previously used nomenclature[16,17] (**Fig. 2d**).

To further validate our findings, we took advantage of published in situ hybridization results available via the Mouse Genome Informatics (MGI) database. We downloaded a list of genes that are detected in the pulmonary mesenchyme from *E*11.5 to *E*12.5 and classified them by expression pattern (**Supplementary Table 3**). We then focused on those that were clearly sub-epithelial or sub-mesothelial and that were detected at sufficient levels in our scRNA-seq dataset. Unsupervised clustering of mesenchymal cells based on their expression of region-specific genes showed that sub-epithelial cells group together and have similar expression of sub-epithelial markers and, likewise, that sub-mesothelial cells group together and have similar expression of their corresponding markers (**Fig. 2e**). UMAPs color-coded according to the summed expression of either sub-epithelial or sub-mesothelial genes show that the two sets of markers are expressed by cells in complementary regions of the UMAP (**Fig. 2f**). We conclude that our computationally identified clusters represent spatially distinct compartments.

We next asked whether these mesenchymal compartments persist over the pseudoglandular stage of lung development. Lef1^{+} cells are detected in the sub-epithelial mesenchyme around branch tips and Foxp1^{+} cells are detected in the sub-mesothelial mesenchyme at *E*12.5 and *E*14.5 (**Supplementary Fig. 3c-e**). Individual Foxp1^{+} cells are also visible in the mesenchyme in

between branches, where they likely represent vascular endothelial cells (**Fig. 2c, Supplementary Fig. 3d, f**). Therefore, the lung maintains a sub-epithelial, Lef1^{+} mesenchymal population and a sub-mesothelial, Foxp1-mesenchymal population over the course of branching morphogenesis. The mesenchyme in between branches (with low Lef1 and Foxp1 immunostaining) may take on new characteristics, perhaps to support formation of vasculature.

Wnt signaling regulates cell identity in the embryonic pulmonary mesenchyme

We hypothesized that the mesenchymal populations identified in our scRNA-seq dataset represent cell types with important functions in branching morphogenesis. Indeed, GO enrichment analysis of genes upregulated in each mesenchymal cluster revealed that both clusters are enriched for genes involved in "morphogenesis of a branching epithelium" (**Fig. 3a, Supplementary Tables 2, 4**). Additionally, our analysis revealed a significant enrichment of genes with GO terms related to Wnt signaling. We therefore examined differentially-expressed Wnt signaling-related genes (**Fig. 3b**). Among the genes upregulated in the sub-epithelial cluster were Lef1, a Wnt signaling effector[31], and Wnt2, a Wnt ligand implicated in airway smooth-muscle differentiation[23]. Overall, the sub-epithelial cluster expresses more activators and targets of Wnt signaling, while the sub-mesothelial cluster expresses more inhibitors. Each mesenchymal cluster is therefore characterized by a distinct Wnt-signaling signature and, consistent with previous studies[19,20,32], the sub-epithelial cluster may be more Wnt-active.

Signals from the epithelium and mesothelium have previously been shown to regulate behaviors of the sub-epithelial and sub-mesothelial mesenchyme, respectively[16,17]. We therefore

hypothesized that Wnt signals from these tissues could establish compartments of differential Wnt signaling across the epithelium-to-mesothelium axis. Tissue-specific analysis using our scRNA-seq dataset confirmed that the epithelium expresses *Wnt7b* and the sub-epithelial mesenchyme expresses *Wnt2*[19] (**Fig. 3c**). The sub-mesothelial mesenchyme expresses *Wnt11*, the mesothelium expresses *Wnt9a*, and both tissues express the inhibitors *Sfrp1* and *Sfrp2*, suggesting that Wnt signaling may be inhibited at the mesothelial end of the axis (**Fig. 3c**). Vascular-endothelial and smooth-muscle cells do not show any striking expression patterns of Wnt ligands or secreted inhibitors. *Fzd1* and *Fzd2* are the only Wnt receptors detected in the mesenchyme, but they are not preferentially enriched in either cluster (**Fig. 3c**), suggesting that differential Wnt signaling across the mesenchyme arises from patterned expression of ligands and inhibitors.

To determine whether Wnt signaling can regulate the compartments of the pulmonary mesenchyme, we manipulated this pathway in lungs explanted from *E*11.5 CD1 mouse embryos. To activate Wnt signaling, we inhibited GSK3 by treating lung explants with LiCl[20], which maintains nuclear β-catenin levels and increases cytoplasmic Axin2 intensity in the mesenchyme (**Supplementary Fig. 4**). Conversely, to downregulate Wnt signaling, we treated explants with IWR1, which stabilizes Axin2 leading to enhanced activity of the β-catenin destruction complex[20]. As expected given its mechanism of action, IWR1 treatment does not affect Axin2 intensity, but reduces nuclear β-catenin intensity in the mesenchyme (**Supplementary Fig. 4**).

We then quantified the domains of Lef1$^+$ sub-epithelial cells and Foxp1$^+$ sub-mesothelial cells. We plotted Lef1-intensity profiles as a function of distance from the tip of the epithelial branch L.L2 (the second domain branch of the left lobe, which initiates and extends during the culture period[9,33]) and Foxp1-intensity profiles as a function of distance from the mesothelium. LiCl-treated explants show an expanded domain of Lef1$^+$ cells around epithelial branch tips and fewer Foxp1$^+$ cells than DMSO-treated controls (**Fig. 3d-g**). Conversely, IWR1-treated explants exhibited a signficant reduction in Lef1 intensity and a random distribution of Foxp1$^+$ cells in the mesenchyme adjacent to the tip of branch L.L2 (**Fig. 3d-g**). Overall, activating Wnt signaling expands the sub-epithelial mesenchyme at the expense of the sub-mesothelial mesenchyme, and inhibiting Wnt shrinks the sub-epithelial compartment. Consistently, enhancing Wnt signaling via mesenchymal deletion of the Wnt-inhibitor Adenomatous polyposis coli (*Apc*) results in increased expression of the sub-epithelial mesenchymal marker versican (*Vcan*)[22] and inhibiting Wnt signaling via mesenchymal deletion of *Ctnnb1* results in decreased expression of the sub-epithelial mesenchymal markers *Lef1* and cyclin D1[21] (*Ccnd1*; **Supplementary Table 2**).

To determine whether mesenchymal patterning also depends on Shh, we treated explants with the Shh antagonist cyclopamine, which prevents smooth-muscle differentiation and decreases sub-epithelial mesenchymal cell proliferation[9,16]. In the presence of cyclopamine, the Lef1$^+$, sub-epithelial domain is reduced around branch tips, but the Foxp1$^+$ sub-mesothelial domain is slightly expanded (**Fig 3h-k**). We then asked whether Wnt or Shh could override each other's compartment-specific effects. We combined cyclopamine and LiCl treatments and found that activating Wnt signaling rescues the loss of Lef1$^+$ cells caused by Shh inhibition (**Fig. 3l, n**). However, Foxp1 intensity is much lower than controls and similar to LiCl treatment alone (**Fig.**

3m, o), suggesting that the positive effects of Shh inhibition on this compartment are indirect and cannot overcome the effects of activated Wnt signaling.

Mesenchymal cell motility and cortical forces are spatially patterned during airway branching morphogenesis

Our observations thus far suggest that the two mesenchymal clusters represent a continuum of cell states that can be shifted by Wnt signaling instead of two distinct tissues. We therefore investigated whether mesenchymal cells transition between compartments and/or into the smooth-muscle lineage. We used Dermo1-Cre driven expression of R26R-Confetti to sparsely label mesenchymal cells and performed time-lapse imaging analysis of lung explants isolated at *E*11.5. Dermo1-Cre is active throughout the pulmonary mesenchyme[16] (**Supplementary Fig. 5a**), including in Lef1^{+} sub-epithelial and Foxp1^{+} sub-mesothelial mesenchymal cells (**Fig. 4a-b**). Confetti-labelled cells were observed to elongate around epithelial buds (**Supplementary Fig. 5b**) and could contribute to the smooth-muscle layer (**Fig. 4c**). Strikingly, Confetti-labelled cells are not clustered within groups of clones, suggesting that mesenchymal cells rearrange extensively during branching morphogenesis (**Supplementary Fig. 5b**). Indeed, mesenchymal cells are suprisingly motile (**Supplementary Video 1**), and cell tracking and mean squared displacement (MSD) analyses showed that mesenchymal cells exhibit a range of migratory behaviors, from sub-diffusive to directed (**Supplementary Fig. 5c-h**). Migration speeds are highly variable and are greatest among sub-epithelial mesenchymal cells (**Fig. 4d**), demonstrating that cell motility differs between mesenchymal compartments.

We observed that mesenchymal cells can move between compartments over short timescales (~5 hours) relative to the timescales of branching in ex vivo culture (~20 hours). The majority stay within their compartments over the timescales analyzed, but a fraction of cells cross over into the opposite compartment (**Fig. 4e-h**), possibly contributing to the continuum of mesenchymal cell transcriptional states. Most tracked smooth-muscle cells were already elongated around the epithelium, but some originated from rounder, sub-epithelial cells at branch tips (**Fig. 4h-j**). Consistent with previous work in fixed tissues[18], our time-lapse data show that smooth-muscle cells arise from the sub-epithelial mesenchyme.

Cell migration and rearrangements are regulated by cortical tension, which can be estimated using the FRET-based vinculin tension sensor (VinTS)[34] (**Fig. 4k**). A VinTS knock-in mouse was recently generated and validated to infer cortical forces in mandibular arch morphogenesis[35]. Live-imaging and fluorescence lifetime imaging microscopy (FLIM) of *E*12.5 VinTS lungs revealed that the epithelium and sub-epithelial mesenchyme had the longest average fluorescence lifetimes (highest tension), while the vasculature had the lowest (**Supplementary Fig. 5i-j**). Consistent with the observed differences in migratory behavior[35], we found that sub-epithelial mesenchymal cells had higher and more variable fluorescence lifetimes than sub-mesothelial mesenchymal cells (**Fig. 4l-m**). Further, these data suggest that sub-epithelial cells experience higher cortical tension. Altogether, our data show that the two transcriptionally-distinct mesenchymal compartments have different migratory behaviors and mechanical properties.

Sub-mesothelial mesenchymal cells may give rise to vascular smooth muscle

Our data show that the sub-epithelial mesenchyme gives rise to airway smooth muscle, but computational clustering suggests that the sub-mesothelial mesenchyme is also closely related to smooth muscle. We hypothesized that the sub-mesothelial mesenchyme could give rise to vascular smooth-muscle cells. Mature vascular smooth muscle is not yet present in the lung at *E*11.5[36], but there could be cells in early stages of differentiation down this lineage. We therefore examined the levels of markers enriched in either airway or vascular smooth muscle[3] (**Supplementary Fig. 6a**). The expression of airway smooth-muscle genes is highest in the smooth-muscle cluster (**Supplementary Fig. 6b-f**). Among these, *Foxf1*, *Mylk* and *Nog* are enriched in sub-epithelial compared to sub-mesothelial mesenchyme, as expected given that sub-epithelial mesenchyme gives rise to airway smooth muscle. Conversely, the vascular smooth-muscle markers *Heyl* and *Speg* are slightly enriched in the sub-mesothelial mesenchyme (**Supplementary Fig. 6g-h**), suggesting that this compartment might contain vascular smooth-muscle precursors. Clustering of smooth-muscle cells alone did not reveal a distinct vascular smooth-muscle population (**Supplementary Fig. 6i-p**). We therefore examined lungs at *E*14.5, when vascular smooth muscle is easily detected around blood vessels, and observed that vascular smooth-muscle cells are Lef1^{-} and Foxp1^{+} (**Supplementary Fig. 6q-s**), suggesting that Foxp1^{+}, sub-mesothelial mesenchyme may differentiate into vascular smooth muscle.

Diffusion analysis of mesenchymal cells provides insight into differentiation trajectories

Our scRNA-seq dataset is comprised of undifferentiated mesenchymal cells and mature smooth-muscle cells, and theoretically should include cells at every stage of differentiation between these two states. Live-imaging revealed that smooth-muscle cells originate from the sub-epithelial mesenchyme (**Fig. 4**). We therefore focused on transitions from the sub-epithelial

mesenchymal cluster to the smooth-muscle cluster. To search for differentiation trajectories, we implemented diffusion analysis using the Destiny package[27]. Undifferentiated sub-epithelial mesenchymal cells are separated from smooth-muscle cells along diffusion component (DC) 1 (**Fig. 5a**). The expression of smooth muscle-related genes is positively correlated with DC1, and gene number, a powerful indicator of cell developmental potential[37], is negatively correlated with DC1 (**Fig. 5b-c**), suggesting that progression along DC1 represents cells moving away from a stem-cell-like state and differentiating into smooth muscle.

To determine how gene expression evolves over the course of airway smooth-muscle differentiation, we fit the expression of each gene along DC1 and applied unbiased clustering to group genes with similar profiles. We focused on four resultant gene sets that increased along DC1 and one that decreased (**Fig. 5d, Supplementary Table 6**). The upregulated gene sets (1-4, numbered from latest to earliest) included genes related to smooth muscle and to Wnt, Shh, TGFβ, Bmp, and Hippo signaling pathways, and the downregulated set (5) included the mesenchymal progenitor marker *Tbx2* and the distally-expressed ligand *Wnt2*, suggesting that our analysis had yielded biologically relevant gene sets.

To identify signaling pathways implicated along the smooth-muscle differentiation trajectory, we used KEGG pathway enrichment analysis and carried out motif discovery in promoter and DNase-hypersensitive regions (indicative of accessible chromatin) proximal to genes of each set (**Fig. 5e-f, Supplementary Fig. 7**). Consistent with our hypothesis that DC1 recapitulated smooth-muscle differentiation, we found that Srf-binding sites (CArG boxes) are highly enriched

in the promoters and DNase-hypersensitive regions of genes in sets 2 and 3 (**Fig. 5f**). Further, we found binding sites for Foxf1, a regulator of airway smooth-muscle differentiation[38], in DNase-hypersensitive regions near genes of set 3 (**Fig. 5f**). We also identified binding sites for the mesenchymal-compartment markers Lef1 and Foxp1 near genes of sets 2, 3, and 4 (**Fig. 5f**).

All gene sets together, and in particular those that increased in expression along DC1, are enriched for genes involved in Wnt, TGFβ, Hippo, Hedgehog, and MAPK signaling (**Fig. 5e**). Accordingly, we found motifs for binding sites of Smad-family transcription factors in promoters of genes in set 3, and of Tcf- and Tead-family members in DNase-hypersensitive regions near genes in sets 2-5 (**Fig. 5f**). Nearly all of these pathways have been implicated in airway smooth-muscle differentiation, with the exception of Hippo signaling. We therefore deleted the Hippo pathway effector Yap1 in the embryonic mesenchyme using Dermo1-Cre and isolated lungs at *E*12.5. Markers for the sub-epithelial and sub-mesothelial compartments are greatly reduced, as is smooth-muscle wrapping (**Fig. 6a**), demonstrating that Yap1 is required for patterning and differentiation in the embryonic pulmonary mesenchyme. Our computational analyses can therefore be used to uncover novel signaling pathways important for lung development.

Differentiating mesenchymal cells undergo changes in cell contractility and adhesion to elongate and wrap around the epithelium[3]. Our analyses revealed that genes related to the cytoskeleton, cell adhesion, and the extracellular matrix are upregulated early during differentation, and that their expression accompanies or precedes the expression of the smooth muscle-specific machinery (*Acta2*) and transcription factors (*Myocd*) (**Fig. 5e, Fig. 6b**). These

data suggest that gene expression in differentiating smooth-muscle cells may be *Myocd*-independent. In line with this, only a minor fraction (0-6%) of the smooth-muscle genes identified using diffusion analysis (**Fig. 5d**) and of smooth-muscle cluster markers (11%) (**Fig. 1d**) are differentially expressed in a bulk RNA-seq dataset of *E*13.5 lungs in which *Myocd* is deleted from the mesenchyme[11] (**Supplementary Fig. 8**). Overall, these data show that the airway smooth muscle gene-expression program is largely *Myocd*-independent.

Finally, we found that genes that decrease along the smooth-muscle differentiation trajectory are associated with metabolic pathways (**Fig. 5e**), and that genes involved in proliferative metabolism and biomass production are downregulated along DC1 (**Fig. 6c**). Indeed, Myc- and Mycn-binding sites are enriched in DNase-hypersensitive regions near genes of set 5 (**Fig. 5f**), suggesting that proliferativ gene expression is downregulated during differentiation. Additionally, binding sites for Foxk1 and Foxk2, regulators of glycolysis[39], are present in the promoters and DNase-hypersensitive regions of gene sets 3 and 4 (**Fig. 5f**). Overall, our analyses uncover a possible role for metabolic reprogramming during smooth-muscle differentiation.

Wnt signaling activates the early stages of smooth-muscle differentiation to influence epithelial branching

Our computational analyses suggested that Wnt signaling may be involved in the early stages of airway smooth-muscle differentation. We therefore evaluated the effects of manipulating Wnt signaling on smooth-muscle coverage (percentage of the circumference of the left bronchus wrapped by αSMA^+ smooth muscle) in LiCl- and IWR1-treated explants. Neither treatment

signicantly affected smooth-muscle coverage (**Fig. 7a-c**). Genetic strategies to activate or inhibit Wnt signaling in the pulmonary mesenchyme both lead to disorganized αSMA$^+$ smooth-muscle wrapping without overtly changing αSMA levels around the airways[17,18]. Overall, these data suggest that manipulating Wnt signaling has very minor effects on αSMA expression.

This finding was surprising, given the similar epithelial morphologies that result from manipulation of mesenchymal Wnt signaling (**Fig. 7d-g**) and from manipulation of smooth-muscle differentiation[9]. LiCl-treatment reduces branching frequency and impedes branch extension, similar to lungs with enhanced smooth-muscle differentiation. Conversely, IWR1-treated lungs have highly variable branching frequencies, buckled epithelial morphology, and wider branches, much like lungs with reduced smooth-muscle differentiation. Similar to the effects of LiCl treatment, *Apc*-deletion to enhance Wnt signaling in the mesenchyme leads to constricted buds without increasing αSMA wrapping[22]. Taken together, these data suggest that αSMA-rich smooth muscle is not driving these changes in branching.

Diffusion analyses suggested that differentiating mesenchymal cells could undergo changes in contractility and stiffness quite early, and perhaps before the robust expression of smooth-muscle markers (**Fig. 7b**). To visualize smooth-muscle cells in the earliest stages of differentiation, we isolated lungs from embryos expressing RFP under the control of the αSMA promoter (SMA-RFP mice). RFP signal can be used to identify nascent smooth-muscle cells that do not have sufficient αSMA for detection by immunofluorescence analysis. Strikingly, we observed a thick layer of F-actin-rich mesenchyme containing many RFP$^+$ cells surrounding

stunted epithelial branches in LiCl-treated explants (**Fig. 7h-i**). These data suggest that Wnt activates the earliest stages of smooth-muscle differentiation. Consistently, genetically activating mesenchymal Wnt signaling leads to widespread expression of *Bmp4*, one of the earliest genes activated along the smooth-muscle differentiation trajectory, and dense mesenchymal-cell packing around the epithelium, preventing branching[22]. Here, we observed that local accumulation of F-actin, indicative of mesenchymal stiffening[40,41], similarly prevented epithelial branch outgrowth.

Discussion

Here, we provide the first single-cell overview of cell identities and transitions in the embryonic pulmonary mesenchyme during branching morphogenesis of the mouse lung. scRNA-seq analyses revealed compartment-specific transcriptional heterogeneity across the mesenchyme and uncovered how signaling pathways evolve over the course of airway smooth-muscle differentiation. Building off of our computational findings, we identify Wnt signaling as a master regulator of mesenchymal patterning in early lung development and show that Wnt-dependent activation of smooth-muscle differentiation and mesenchymal stiffening can physically influence airway epithelial branching.

Our data show that the pulmonary mesenchyme contains a continuum of cell identites, which may explain why a distinct smooth-muscle progenitor marker has remained elusive[25]. Unbiased lineage tracing in fixed samples previously showed that new smooth-muscle cells at branch tips are members of clones from the adjacent sub-epithelial mesenchyme[18]. Our live-imaging data

support these findings, and also reveal a surprising level of cell motility within the embryonic pulmonary mesenchyme. Similar dynamic behaviors have been observed in kidney development[42]. The extent and timescales of these rearrangements raise questions about how focal morphogen sources proposed to act as chemoattractants could be maintained as mesenchymal cells migrate during branching morphogenesis[43,44].

The heterogeneity of mesenchymal cells within developing tissues influences how they respond to morphogenetic signals[45] and can define if and when they differentiate. Exposing transplanted stalk mesenchyme to a Wnt signal primes it to migrate into a donor tissue and form smooth muscle[18]. It is possible that stalk mesenchyme is comprised of sub-mesothelial mesenchymal cells, and that activation of Wnt signaling converts them to a sub-epithelial identity, which we have shown here is associated with greater cytoskeletal tension and motility.

We and others have shown that Fgf9/Shh[16] and Wnt signaling spanning the epithelium to the mesothelium patterns the embryonic pulmonary mesenchyme. Epithelium-derived Wnt signals also radially pattern smooth-muscle differentiation in the ureteric mesenchyme[46]. In the chick intestine, opposing molecular signals from the epithelium and the mesothelium, as well as mechanical forces generated by growth of the intestinal epithelium and contraction of smooth muscle, are integrated to spatiotemporally pattern the differentiation of multiple smooth-muscle layers[47]. The role of mechanical forces in regulating pulomonary mesenchymal cell identity have yet to be fully elucidated.

Reconstructing the smooth-muscle differentiation trajectory revealed that genes related to the cytoskeleton and cell-matrix adhesions are expressed early during differentiation. These changes could lead to tissue stiffening, which regulates diverse morphogenetic events[41,48,49]. Indeed, we found that Wnt-dependent accumulation of nascent smooth-muscle cells and F-actin around emerging branches is associated with local inhibition of epithelial growth. Similarly, activating Wnt signaling in the ureteric mesenchyme leads to ectopic accumulation of smooth-muscle progenitors and a hypoplastic ureter[46]. F-actin levels can reflect cell and extracellular matrix stiffening[40,41], and Wnt signaling can activate actomyosin contractility[50] and matrix deposition[19], possibly contributing to tissue stiffening around emerging branches. VinTS experiments revealed higher cortical tension in the sub-epithelial mesenchyme, which may allow it to physically sculpt the branching epithelium. Activation of Wnt signaling to promote sub-epithelial mesenchymal fates could enhance this effect.

Our results raise questions about which stage(s) of smooth-muscle differentiation and which aspects of smooth-muscle cell identity influence branching morphogenesis. The smooth-muscle gene-expression program extends beyond the influence of a single transcription factor (*Myocd*), suggesting that developing smooth muscle may be robust to the loss of single components. Indeed, loss of *Acta2* is compensated for by other actin isoforms[12,13]. In the developing lung, *Myocd*-deletion decreases the expression of only a few smooth-muscle genes, and in the developing ureter, expansion of smooth-muscle progenitors occurs with minimal increase in the expression of *Myocd*[46]. Consistently, *Myocd* expression is insufficient to drive the entire smooth-muscle gene-expression program in cell culture[51].

Our scRNA-seq analyses have uncovered novel regulators of mesenchymal patterning during lung development. We computationally identified and genetically validated a role for Hippo signaling via Yap1 in the embryonic pulmonary mesenchyme. Mesenchymal Yap regulates smooth-muscle differentiation around the gastrointestinal epithelium[52], and crosstalk between Wnt and Yap signaling regulates intestinal stem cell homeostasis[53]. Future investigations will elucidate how Yap influences airway smooth-muscle differentiation and whether cooperation with Wnt signaling is involved. Our data also reveal that sub-epithelial cells systematically downregulate enzymes required for proliferative metabolism as they differentiate into smooth muscle, and that Foxk1/2, regulators of glycolysis[39], may be involved in differentiation. Metabolic reprogramming is a critical component of stem cell maintenance and differentiation[54], and enhanced glycolysis acts via Yap to regulate neural crest migration[55]. Notably, Foxk1 interacts with Srf to repress expression of genes including *Acta2*[56], suggesting that metabolic reprogramming participates in airway smooth-muscle differentiation.

In conclusion, our findings reveal the heterogeneity of the embryonic pulmonary mesenchyme and the multitude of signals involved in smooth-muscle differentiation. Our computational analyses lay the foundation for future investigations into the mechanisms that regulate cell identity and differentiation in the pulmonary mesenchyme. Further, our approaches could be extended to other organs or organisms to compare tissue patterning and differentiation in diverse developmental contexts.

Online Methods

Mice

Breeding of CD1, Dermo1-Cre (JAX 008712), R26R-Confetti (JAX 013731), mTmG (JAX 007676), SMA-RFP, and Yap-flox (JAX 027929) mice and isolation of embryos were carried out in accordance with institutional guidelines following the NIH Guide for the Care and Use of Laboratory Animals and approved by Princeton's Institutional Animal Care and Use Committees. Breeding of VinTS mice[35] and isolation of embryos were carried out in accordance with the Animals for Research Act of Ontario and the Guidelines of the Canadian Council on Animal Care, and procedures were approved by the Hospital for Sick Children Animal Care Committee. Dermo1-Cre/+;Confetti/+ embryos were obtained by mating Confetti homozygous females to Dermo1-Cre heterozygous males. Yap-flox and mTmG mice were bred to generate homozygous Yap-flox;mTmG mice. Dermo1-Cre males were bred to Yap-flox females to generate Dermo1-Cre/+;Yap-fl/+ males, and these were then mated to Yap-flox;mTmG females to generate Dermo1-Cre/+;Yap-fl/fl;mTmG/+ and control Dermo1-Cre/+;Yap-fl/+;mTmG/+ littermates. Pups and embryos from were genotyped for Cre, mTmG, and/or Yap-flox by isolating DNA from the tail snips (pups) or from the head of each embryo, followed by PCR and gel electrophoresis. The forward primer sequence for Cre was GCATTACCGGTCGATGCAACGAGTGATGAG and the reverse primer sequence was GAGTGAACGAACCTGGTCGAAATCAGTGCG. The primer sequences for Yap-flox and mTmG are provided in the Jackson Labs genotyping protocol for each strain. Where possible, mGFP expression from mTmG was used for genotyping.

scRNA-seq experiments

Lungs were dissected from CD1 mouse embryos collected at *E*11.5 in cold PBS. Isolated left lobes were grouped by stage, placed in dispase, and mechanically dissociated with tungsten needles. After 10 minutes in dispase at room temperature, DMEM without HEPES and supplemented with 5% fetal bovine serum (FBS, Atlanta Biologicals) was added, and cell suspensions were passed through a filter with 40-µm-diameter pores. The resultant cell suspensions were then processed by the Princeton Genomics Core Facility. The two sample groups were processed separately. Cells were loaded and processed using the Chromium Single Cell 3' Library and Gel Bead Kit v2 on the Chromium Controller (10X Genomics) following manufacturer protocols. Individual cells were encapsulated in droplets with single gel beads carrying unique barcoded primers and then lysed. Then cDNA fragments were synthesized, barcoded, and amplified by PCR. Illumina sequencing libraries were prepared from the amplified cDNA from each sample group using the Nextra DNA library prep kit (Illumina). The v2 libraries were sequenced on Illumina HiSeq 2500 Rapid flowcells (Illumina) as paired-end 26 + 50 nucleotide reads following manufacturer protocols. Base calling was performed, and raw sequencing reads were filtered using the Illumina sequencer control software to keep only pass-filtered reads for downstream analysis. The 10x CellRanger software version 2.0.1 was used to run the count pipeline with default settings on all FASTQ files from each sample to generate gene-barcode matrices using the *Mus musculus* reference genome mm10-1.2.0.

scRNA-seq data analysis

scRNA-seq data exported from Cell Ranger were imported into R and processed using the Seurat package[28]. Datasets from all groups were normalized and then integrated based on 2000 variable features (genes) identified by the Seurat function FindVariableFeatures. The

integrated dataset was then scaled and analyzed to find neighbors and clusters with the Seurat functions FindNeighbors and FindClusters. Finally, the uniform manifold approximation and projection (UMAP) dimensional reduction was performed to visualize clusters. For initial analyses, all cells were used, which revealed large clusters of blood and immune cells (**Supplementary Fig. 1k-l**). Since these were not the cell populations of interest, we removed them from further analysis (**Supplementary Fig. 1m-n**). We then adjusted the dataset to account for cell-to-cell variability based on cell-cycle stage using the Seurat package. The resulting filtered and adjusted dataset was used for all subsequent analyses. Cluster identities were then assigned based on markers enriched in each cluster that are known to be enriched in each lung cell population. To investigate mesenchymal cells specifically, we repeated the Seurat pipeline outlined above including only cells from clusters 0, 1, and 2 (**Supplementary Fig. 2**). We generated a UMAP, identified markers for each of the 5 new clusters identified, and examined the expression of putative progenitor markers in each cluster (**Supplementary Fig. 2**).

Using published in situ hybridization results available on MGI, we compiled a list of genes that have been detected in the pulmonary mesenchyme at *E*11.5-*E*12.5. Based on MGI entries containing images, we classified the expression pattern of each gene as either sub-epithelial, sub-mesothelial, smooth muscle, everywhere, or weak (**Supplementary Table 3**). Genes that did not fit any of these broad categories because of even more limited expression domains were excluded. A subset of the genes classified as sub-epithelial or sub-mesothelial were detected and included as variable features by the Seurat algorithm. Using the heatmap.2 function in R, we clustered sub-epithelial and sub-mesothelial cells based on their expression of

this subset of genes (columns in **Fig. 2e**) and clustered the genes from the curated MGI list (rows in **Fig. 2e**).

To search for functional differences between the mesenchymal clusters identified in **Fig. 1**, we identified genes that were differentially expressed in cluster 0 compared to cluster 1 using the FindMarkers function from the Seurat package, and then grouped these based on whether they were upregulated in cluster 0 or in cluster 1. These gene lists were then subjected to GO enrichment analysis using the clusterProfiler package in R[57].

Diffusion analysis of mesenchymal cells

To reconstruct smooth-muscle differentiation trajectories, we used the cell-by-gene matrix of 2000 variable genes with scaled expression values generated using the Seurat algorithm and applied the Destiny package in R[27]. Only clusters 0 and 2 were used in this analysis. Three cells from cluster 0 appeared as clear outliers and were excluded from this analysis. To search for groups of genes with similar expression patterns over the course of smooth-muscle differentiation, we first used the edgeR package in R to fit the expression of all genes along DC1 using a spline model with three degrees of freedom[58]. The resulting fits were then filtered by adjusted p value < 0.05 obtained by implementing a generalized likelihood ratio test with the lrt function from the edgeR package[58]. These fits were then clustered using hierarchical agglomerative clustering with average linkage based on Pearson correlation distance to identify gene sets with similar expression profiles along DC1. Gene sets of interest were then subjected to KEGG pathway enrichment analysis implemented using clusterProfiler[57].

Motif discovery

Motif discovery was carried out by examining promoter regions and DNase-hypersensitive regions near genes of interest using a custom Python pipeline and HOMER[59]. Genomic regions based on the mouse ENCODE *E*14 lung DNase-hypersensitivity dataset[60] were matched to genes from the gene sets identified in **Fig. 5d** based on proximity to their transcriptional start site. The sequences of these DNase-hypersensitive regions were then extracted and analyzed using HOMER findMotifs.pl FASTA motif analysis tool[59] to identify overrepresented motifs compared to a background file of DNase-hypersensitive regions located near the transcriptional start sites of a list of genes randomly generated with the Regulatory Sequence Analysis Tools (RSAT) web interface[61].

Organ explant culture and live imaging

Lungs from *E*11.5 CD1 mice were dissected in cold, sterile PBS supplemented with antibiotics (50 units/ml of penicillin and streptomycin) and then cultured on porous membranes (nucleopore polycarbonate track-etch membrane, 8 µm pore size, 25 mm diameter; Whatman) floating on top of DMEM/F12 medium (without HEPES) supplemented with 5% FBS and antibiotics (50 units/ml of penicillin and streptomycin) for 24 hr. Reagents used to manipulate Wnt signaling included LiCl (10 mM; Sigma) and IWR1 (100 µM; Sigma). To inhibit Shh signaling we used cyclopamine (1 µM; Tocris). For live-imaging analysis, Dermo1-Cre/+;Confetti/+ lungs were cultured on Transwell filters (polyethylene terephthalate membrane, 3 µm pore size, 10.5 mm diameter; Corning) within a stage-top incubator (Pathology Devices). Frames were acquired every 30 or 60 min for up to 48 hr under brightfield (1-2 ms exposure per

plane for a total of seven planes per time point) or spinning disk confocal illumination (X-light, 122 ms exposure per plane for 5-7 planes per time point) on an inverted microscope (Nikon Ti).

Vinculin tension sensor experiments

Lungs were isolated from *E*12.5 VinTS embryos and embedded in 1% low melting point agarose on a coverslip fitted into a custom imaging chamber. After an hour of incubation at 37°C, cell culture medium supplemented with 5% FBS was added to the chamber and samples were imaged by confocal and fluorescence lifetime microscopy (FLIM). Imaging and analyses were performed as previously described[35]. Briefly, FLIM was carried out on a Nikon A1R Si laser-scanning confocal microscope with a PicoHarp 300 TCSPC module and a 440 nm pulsed-diode laser (Picoquant). Imaging was performed with a 40×/1.25 NA water immersion objective. For each lung, 2 to 3 z-stacks at different locations along the distal left lobe were acquired. Fluorescence lifetime of the donor fluorophore (mTFP1) was estimated using FLIM Fit 5.1.1[62]. Cells of interest were segmented manually in FLIM Fit to obtain an average lifetime per cell. Sub-epithelial mesenchymal cells were at least 2-cell bodies away the from the mesothelium, and sub-mesothelial mesenchymal cells were within 2-cell bodies of the mesothelium.

Tissue sectioning, immunofluorescence analysis, and imaging

Isolated lungs were fixed in 4% paraformaldehyde in PBS for 15 minutes at room temperature. For sectioning, lungs were washed first in 20% sucrose in PBS, then 30% sucrose in PBS, then left overnight in a 1:1 mixture of OCT and 30% sucrose prior to embedding and freezing in OCT. A Leica CM3050S cryostat was then used to create 10-µm-thick sections for

staining on slides. For whole-mount staining and for sections on slides, samples were washed with 0.1% Triton X-100 in PBS and then blocked with 5% goat serum and 0.1% BSA. Samples were then incubated with primary antibodies against αSMA (Sigma a5228, 1:400), Axin2 (Abcam ab32197, 1:200), β-catenin (Sigma SAB4500541, 1:200), E-cadherin (Cell Signaling 3195, 1:200 or Invitrogen 13-1900, 1:200), Foxp1 (Cell Signaling 2005, 1:200), GFP (Invitrogen A-11122, 1:500), Lef1 (Cell Signaling 2230, 1:200), PECAM (Abcam ab28364, 1:200), or RFP (Abcam ab62341, 1:400), followed by incubation with Alexa Fluor-conjugated secondary antibodies (1:200), Alexa Fluor-conjugated phalloidin (1:500) and/or Hoechst (1:1000). Sections on slides were then mounted in Fluorosave. Whole lungs were dehydrated in a methanol series and cleared with Murray's clear (1:2 ratio of benzyl alcohol to benzyl benzoate). To preserve endogenous fluorescence of Confetti and VinTS lungs, samples were not dehydrated or cleared, but instead mounted in Fluorosave. Confocal stacks were collected using a spinning disk confocal (BioVision X-Light V2) on an inverted microscope (Nikon Ti) using either 20× air, 40× oil, or 60× oil objectives (Nikon).

Image analysis and statistics

We developed a simple pipeline in MatLab to quantify fluorescence intensity profiles. First, images of Lef1 or Foxp1 immunostaining were background subtracted and then lines were traced either starting at the edge of branch L.L2 and moving outward into the mesenchyme for Lef1 or starting at the mesothelium near branch L.L2 and moving inward into the mesenchyme for Foxp1. Average fluorescence intensity in a 16 × 16 pixel window (5.7 × 5.7 μm) was measured at each point along the line, and the calculation included only the intensity of pixels within cell nuclei based on a mask generated from Hoechst staining. Intensity profiles were

averaged from 5 distinct lines per sample, and the resultant curves were compared using two-way ANOVA in GraphPad Prism 5. A similar pipeline was used to quantify Axin2, β-catenin, and F-actin intensity, with small modifications. Axin2 intensity was only averaged from regions with no Hoechst signal, and β-catenin levels were compared as the ratio of mean nuclear ($Hoechst^+$) to mean cytoplasmic ($Hoechst^-$) pixels. F-actin intensity was measured from all pixels (no mask).

Smooth-muscle coverage was quantified as described previously[9]. Briefly, the outline of the epithelium was traced in reconstructed cross-sections through the left primary bronchus at 5 different planes, and αSMA fluorescence intensity was measured in a 16×16 pixel (5.7×5.7 μm) window at each point along the outline. Percent coverage was defined as the percentage of the epithelial outline with above-threshold αSMA staining intensity. Sample groups were compared using a two-sided t-test in GraphPad Prism 5.

Time-lapse analysis

Cells from time-lapses of Dermo1-Cre/+;Confetti/+ embryos were tracked manually in Fiji for as many consecutive time points as possible, and the resultant tracks were analyzed in MatLab. To estimate cell speeds, we first corrected cell tracks for local tissue movement and drift. Since the direction and magnitude of lung growth depends on location within the organ, we corrected cell tracks based on local displacements: for each cell, we computed the mean displacement of all cells within a 150 pixel (111 μm) radius as an estimate of local tissue movement, and then subtracted the cumulative sum of these displacements from the original cell's track at each time point. This approach allowed us to independently correct for proximal-

distal movements near the elongating primary bronchus and lateral movements near expanding branch tips (see tracks for smooth-muscle cells vs. sub-epithelial and sub-mesothelial mesenchymal cells in **Supplementary Fig. 5d**). Corrected tracks had slightly smaller instantaneous speeds and much smaller overall displacements (**Supplementary Fig. 5e-f**), indicating that our approach had removed the effects of drift and tissue growth. MSD curves for each tracked cell were generated based on time intervals of up to 7 hours and fit with a 1st degree polynomial to estimate persistence. Only fits with R^2 greater than 0.4 were included in the comparison between samples. To generate the pie charts in **Fig. 4**, cells were assigned to a tissue compartment (sub-epithelial mesenchyme, sub-mesothelial mesenchyme, or smooth muscle) based on their location at the start of their track, and classified as staying within their compartment or crossing over by comparing the entire track to tissue growth in the brightfield channel. The boundary between sub-epithelial and sub-mesothelial mesenchyme was between 2- and 3-cell bodies away from the mesothelium. Cells were classified as differentiating into smooth muscle based on their positions and their progressively elongating morphology.

Analysis of bulk RNA-seq of Myocd-mutant lungs

Bulk RNA-seq data for 5 control and 5 mutant *E*13.5 lungs in which Myocd had been deleted from the mesenchyme were downloaded from GEO (accession number GSE143394[11]) and processed using the DESeq2 package[63]. Briefly, the DESeq2 package was used to import data, estimate size factors and dispersions, and then calculate differential expression of genes and significance using the Wald test. Log fold changes were shrunk according to the DESeq2 package guidelines. We then used volcano plots to visualize adjusted *p*-values and $\log_2$ fold changes for either genes that correlated positively (sets 1-4) or negatively (set 5) with DC1 in

Fig. 5d (**Supplementary Fig. 8a**) or smooth-muscle cluster marker genes from **Fig. 1b, d** (**Supplementary Fig. 8c**). Since most of the genes were not significantly differentially expressed, we also plotted adjusted *p*-values against the mean of regularized log transformed counts obtained using the DESeq2 package to confirm that these genes were detected at high enough levels in the bulk RNA-seq dataset and found that there was no bias of differential expression based on transcript abundance (**Supplementary Fig. 8b, d**).

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Author Contributions

K.G. and C.M.N. conceptualized the study, designed the experiments, intepreted the data, and wrote the manuscript. K.G. performed the experiments and collected the data. J.M.J. carried

out the motif discovery analysis. H.T., M.Z., and S.H. provided all reagents and technical assistance for obtaining VinTS results. All authors provided input on the final manuscript.

Competing interests

The authors declare no competing interests.

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Figure legends

Figure 1. Clustering scRNA-seq data from *E*11.5 mouse lungs reveals expected cell populations. (**a**) Image of sample lung used for scRNA-seq experiment. Each lung was micro-dissected to isolate the left lobe (indicated by dotted outlines). Scale bar shows 100 µm. (**b-c**) UMAP plots of cell cycle-corrected embryonic lung cells isolated by scRNA-seq of *E*11.5 CD1 mouse lungs, color-coded either by cluster (b) or by replicate (c). (**d**) UMAP plots from (b-c) color-coded to show the expression of population-specific genes. (**e**) Top 20 markers for each cluster shown in Fig. 1b based on log fold-change (FC) and color-coded by adjusted p-value.

Figure 2. Computationally identified mesenchymal clusters represent spatially distinct populations. (**a-b**) *E*11.5 lungs immunostained for cluster 0 marker Lef1 (a) or for cluster 1 marker Foxp1 (b) and counterstained with Hoechst. Scale bars show 50 µm. (**c**) Violin plots showing the expression of *Lef1* or *Foxp1* in each cluster. (**d**) Schematic depicting the sub-epithelial and sub-mesothelial compartments of the mesenchyme. (**e**) Heatmap showing the expression of genes specific to either mesenchymal compartment. Genes (rows) are clustered based on the dendrogram to the right. Cells (columns) are clustered based on the dendrogram above, and each column is color-coded according to original cluster identity from Fig. 1b. (**f**) UMAP of mesenchymal and smooth muscle cells color-coded according to the sum of their expression of either sub-epithelial or sub-mesothelial mesenchyme marker genes.

Figure 3. Wnt signaling regulates cell identity in the embryonic pulmonary mesenchyme. (**a**) Bubble plot showing the enrichment percentage and adjusted p-value of relevant GO terms identified based on genes upregulated in each mesenchymal compartment. (**b**) Heatmap showing the expression of Wnt-associated genes upregulated in either mesenchymal cluster. Activators and targets are colored in green, inhibitors are colored in orange. (**c**) Heatmap showing the

expression of Wnt ligands, secreted inhibitors, and receptors detected in either mesenchymal cluster and in clusters containing cells from the mesothelium (meso), vascular endothelium (ve), epithelium (ep), and smooth muscle (sm). (**d-g**) Confocal sections and quantifications of Lef1 and Foxp1 intensity profiles around branch L.L2 in lungs isolated at *E*11.5 from CD1 embryos and immunostained for Lef1 or Foxp1 after treatment with either DMSO, LiCl (10 mM), or IWR1 (100 µM) for 24 hr (n=2-6). (**h-k**) Confocal sections and quantifications of Lef1 and Foxp1 intensity profiles around branch L.L2 in lungs isolated at *E*11.5 and treated with DMSO or cyclopamine (1 µM) for 24 hr (n=4-5). (**l-o**) Confocal sections and quantifications of Lef1 and Foxp1 intensity profiles around branch L.L2 in lungs isolated at *E*11.5 and treated with DMSO or a combination of cyclopamine and LiCl for 24 hr (n=2-3). Yellow dashed lines indicate border of the epithelium. Schematics show lines and direction along which intensity profiles were measured. Mean and s.e.m. are plotted, and curves were compared using two-way ANOVA. Scale bars show 25 µm. * indicates $p<0.05$, ** indicates $p<0.001$, and *** indicates $p<0.0001$.

Figure 4. Embryonic pulmonary mesenchymal cells exhibit spatially patterned migratory behaviors and cortical tension. (**a-c**) Confocal sections of Dermo1-Cre/+;Confetti/+ lungs isolated at *E*11.5, cultured for 48 hrs under time-lapse conditions, and immunostained for Lef1, Foxp1, or αSMA and GFP. (**d**) Mean speed of tracked cells of each mesenchymal cell type (n=6 time-lapses, n=280 cells total). Error bars show s.d. (**e-h**) Snapshots from time-lapse analysis showing a mesenchymal cell migrating from the sub-mesothelial to the sub-epithelial mesenchyme (e) and vice versa (g), and percentage of tracked cells from the sub-mesothelial (f) or the sub-epithelial (h) mesenchyme that stay within their original compartment, cross compartments, or elongate, presumably differentiating into smooth muscle. (**i**) Snapshots from time-lapse analyses of Dermo1-Cre/+;Confetti/+ lungs isolated at *E*11.5 showing sub-epithelial

mesenchymal cells differentiating into smooth muscle. (**j**) Percentage of tracked smooth-muscle cells that were already smooth muscle or that were observed to differentiate from sub-epithelial mesenchymal cells. Yellow arrowhead indicates tracked cell, dashed line indicates the epithelium and dotted line indicates the mesothelium. (**k**) Schematic of VinTS. Vh is vinculin head, Vt is vinculin tail. (**l**) Fluorescence intensity of VinTS in *E*12.5 lung and lifetime of TFP donor along mesenchymal cell edges. (**m**) Fluorescence lifetime of sub-epithelial and sub-mesothelial mesenchymal cells (n=6 samples, n=261-282 cells). Box shows 25th and 75th percentiles, center line shows median. Scale bars show 50 µm. Groups were compared using two-sided t-test and Bartlett's test for unequal variances. *** indicates $p<0.0001$ for t-test and $^{\#}$ indicates $p<0.05$, $^{\#\#}$ indicates $p<0.001$, and $^{\#\#\#}$ indicates $p<0.0001$ for Bartlett's test.

Figure 5. Diffusion analysis reveals differentiation trajectory of mesenchymal cells into airway smooth muscle. (**a**) Diffusion plots of sub-epithelial mesenchymal and smooth-muscle cells. (**b**) Scaled expression of known smooth-muscle genes versus cell loadings along DC1. (**c**) Number of genes detected per cell versus DC1. (**d**) Heatmap showing 5 gene sets identified using hierarchical agglomerative clustering of spline-fitted gene-expression profiles along DC1. Genes of interest are indicated to the right. (**e**) Bubble plot showing the enrichment percentage and adjusted p-value of relevant KEGG pathways for the gene sets defined in e. (**f**) Bubble plot showing the p-values of motifs for transcription factor-binding sites in the promoters of and DNase-hypersensitive regions near genes of sets 2-5. Pearson correlation coefficients and significance are indicated on plots and lines represent smoothed data with standard error shaded in gray. *** indicates $p<0.0001$.

Figure 6. Novel regulators and features of smooth-muscle differentiation. (**a**) Sections of *E*12.5 Dermo1-Cre/+;Yap-fl/fl;mTmG/+ lungs and littermate controls immunostained for GFP

and either Yap1, Lef1, Foxp1, or αSMA. (**b**) Scaled expression of genes involved in cytoskeleton, cell adhesion, and extracellular matrix versus cell loadings along DC1 compared to the expression profiles of smooth-muscle genes *Acta2* and *Myocd* (dotted lines). Pearson correlation coefficients and significance are indicated and lines represent smoothed data with standard error shaded in gray. (**c**) Simplified pathway diagram depicting the steps of proliferative metabolism and showing relevant enzymes at each step. Enzymes that are significantly downregulated along DC1 are indicated in bold red font, with significance of spline fit indicated by asterisks. * indicates $p<0.05$, ** indicates $p<0.001$, and *** indicates $p<0.0001$.

Figure 7. Wnt signaling regulates the accumulation of F-actin and nascent smooth-muscle cells in the sub-epithelial mesenchyme to influence epithelial morphology. (**a**) Confocal sections of the left lobe of lungs isolated from *E*11.5 CD1 embryos and immunostained for E-cadherin (Ecad) and αSMA after treatment with DMSO, LiCl, or IWR1 for 24 hrs. (**b-c**) Quantification of smooth-muscle coverage around the left bronchus proximal or distal to L.L2 (see dashed white lines in a, n=5-10). (**d**) Number of new branches formed in the left lobe after 24 hrs of culture for each treatment condition. (**e**) Schematic showing where branch width and length were measured. (**f-g**) Width and length of L.L2 after 24 hrs of culture for each treatment condition. Error bars show SD. Treatment conditions were compared using one-way ANOVA. (**h**) Confocal sections of the left lobe of lungs isolated from *E*11.5 SMA-RFP embryos and immunostained for RFP and labelled with phalloidin after treatment with DMSO or LiCl for 24 hrs. (**i**) Quantification of F-actin intensity profiles emanating from the epithelium (as depicted in the schematic) for each treatment. Curves were compared using two-way ANOVA. * indicates $p<0.05$ and *** indicates $p<0.0001$.

Supplementary Information

Supplementary Figure Legends

Supplementary Figure 1 – related to Figure 1. scRNA-seq experimental design, summary statistics, and initial clustering. (**a**) Images of all *E*11.5 lungs used for the two replicates of the scRNA-seq experiment. Each lung was micro-dissected to isolate the left lobe (indicated by dotted outlines). Scale bars show 100 µm. (**b**) Table of general statistics for each sample. UMI (unique molecular identifiers) reflects the number of transcripts captured per cell. (**c-d**) UMI counts as a function of number of barcodes for replicates 1 (c) and 2 (d). Portion of curve above threshold includes all cells (green) and portion below is considered background (grey). (**e**) Table of sequencing statistics for each replicate. Q30 statistics give the percentage of bases in the indicated sequence type with a quality score greater than 30. (**f-g**) Sequencing depth as a function of mean reads per cell for each replicate. (**h-i**) Median genes per cell as a function of mean reads per cell. (**j**) Table of mapping statistics for each replicate. Mapping was performed using STAR. (**k-l**) UMAP plot of all cells isolated by scRNA-seq of *E*11.5 CD1 mouse lungs, color-coded by cluster (k) or by replicate (l). (**m-n**) UMAP plot after all blood and immune cells have been removed, color-coded by cluster (m) or by replicate (n).

Supplementary Figure 2 – related to Figure 1. Pulmonary mesenchymal cells are heterogeneous but ultimately closely related. (**a-c**) UMAP plots of isolated mesenchymal cells color-coded to show the expression of key markers from Fig. 1: *Hoxb6*, *Ptn*, and *Acta2*. (**d-g**) UMAP from (a) color-coded to show the expression of putative smooth muscle progenitor markers *Axin2*, *Fgf10*, *Gli1*, and *Wt1*. (**h**) UMAP of mesenchymal and smooth muscle cells corrected for cell-cycle stage and color-coded based on cluster identified by Seurat. (**i-m**) Top 20 marker genes for each cluster based on average log fold-change (FC) and color-coded by

adjusted p-value. (**n-q**) Violin plots showing the expression of putative smooth muscle progenitor markers *Axin2*, *Fgf10*, *Gli1*, and *Wt1* in each of the mesenchymal clusters represented in (h).

Supplementary Figure 3 – related to Figure 2. Lef1 and Foxp1 expression patterns throughout the lung and across developmental stages. (**a-b**) Zoomed-in view of a confocal slice of the left primary bronchus of lungs isolated at *E*12.5 and immunostained for αSMA and either Lef1 or Foxp1. Epithelium indicated by ep. (**c-f**) Confocal slices of the left lobe of lungs isolated at *E*12.5 or *E*14.5 and immunostained for either Lef1 or Foxp1 and counterstained with Hoechst. Scale bars show 50 µm.

Supplementary Figure 4 – related to Figure 3. Manipulating Wnt signaling ex vivo alters levels of Axin2 and β-catenin in the pulmonary mesenchyme. (**a-b**) Sections of lungs isolated at *E*11.5 from CD1 embryos and immunostained for Axin2 or β-catenin and counterstained with Hoechst after treatment with either DMSO, LiCl (10 mM), or IWR1 (100 µM) for 24 hrs. (**c**) Quantification of mean cytoplasmic Axin2 immunofluorenscence intensity in the mesenchyme for each treatment (n=4-11 sections, n=2-3 lungs). (**d**) Quantification of the ratio of nuclear to cytoplasmic β-catenin immunofluorenscence intensity in the mesenchyme for each treatment (n=3-7 sections, n=2-3 lungs). Scale bars show 50 µm. Treatment conditions were compared using one-way ANOVA. * indicates $p<0.05$ and ** indicates $p<0.001$

Supplementary Figure 5 – related to Figure 4. Confetti fluorescent reporters driven by Dermo1-Cre can be used to track single-cell movements in the embryonic pulmonary mesenchyme. (**a**) Confocal slice of the left lobe of lungs isolated at *E*11.5 from a Dermo1-Cre/+;mTmG/+ embryo and immunostained for E-cadherin and GFP. GFP expression throughout the mesenchyme indicates that Cre is active throughout this tissue. (**b**) Snapshots

from time-lapse analysis of Dermo1-Cre/+;Confetti/+ lung isolated at *E*11.5 showing a bifurcating epithelial bud surrounded by sparsely fluorescently-labelled mesenchymal cells. (**c-d**) Snapshots from a time-lapse of Dermo1-Cre/+;Confetti/+ lung isolated at *E*11.5 (c) and plot of cell tracks (d). Tracks colored in gray are uncorrected and tracks colored in blue are corrected for local tissue movement. Cell-type assignments are indicated by the shaded regions. (**e-f**) Distributions of instantaneous speeds from each cell track (e) and of total cell displacements before and after correcting for local tissue movement. (**g**) Log-log plot of mean MSD curves of each mesenchymal cell type. Error bars show s.d. (**h**) Persistence of cell tracks measured as slope of MSD curves from (g). (**i**) Fluorescence lifetime of each lung tissue. Data points represent average per sample. Box shows 25th and 75th percentiles, center line shows median. (**j**) VinTS lung stained for PECAM. Cells with high VinTS expression dispersed throughout the mesenchyme are vascular endothelial cells. Scale bars show 50 µm. Groups were compared using two-sided t-test and Bartlett's test for unequal variances. *** indicates $p<0.0001$ and * indicates $p<0.05$ for t-test. $^{###}$ indicates $p<0.0001$ and $^{\#}$ indicates $p<0.05$ for Bartlett's test.

Supplementary Figure 6 – related to Figure 5. Sub-mesothelial cells may preferentially give rise to vascular smooth muscle cells. (**a**) Table showing the expected expression of each of marker in airway/visceral smooth muscle versus vascular smooth muscle[3]. (**b-h**) Violin plots showing the scaled expression of *Actg2*, *Foxf1*, *Gata5*, *Heyl*, *Mylk*, *Nog*, and *Speg* in each of the mesenchymal and smooth-muscle clusters from **Fig. 1b**. Gene expression per cell cluster compared by Wilcoxon Rank Sum Test using the FindMarkers function. (**i-p**) UMAP of smooth muscle cells computationally isolated from the dataset in **Fig. 1b** color-coded based on scaled expression of marker genes for airway and vascular smooth muscle. (**q-s**) Sections of *E*14.5 lungs immunostained for E-cadherin, αSMA, and either PECAM, Lef1, or Foxp1 and

counterstained with Hoechst. Airway smooth muscle (ASM) and vascular smooth muscle (VSM) are indicated. Scale bars show 50 µm. * indicates $p<0.05$, ** indicates $p<0.001$, and *** indicates $p<0.0001$.

Supplementary Figure 7 – related to Figure 5. Transcription factors identified in motif discovery analysis are expressed in the embryonic lung. Motif logos and tissue-specific expression of corresponding transcription factors for results presented in **Fig. 5f**. For expression of Lef1 and Foxp1, see **Fig. 2c**.

Supplementary Figure 8 – related to Figure 6. The majority of smooth muscle marker genes are Myocd-independent. (**a**) Volcano plot showing the adjusted p-values and log fold changes of gene-set members (**Fig. 5d**) that were detected in bulk RNA-seq of *E*13.5 Myocd-KO lungs compared to controls. Insets to show each gene set separately with the percentage of genes in each quadrant of the volcano plot indicated. (**b**) Adjusted p-values plotted against the mean of regularized log-transformed counts across all samples showing that genes that were not significantly different were detected at similar levels as genes that were significantly different. Points are color-coded according to gene set and insets to the right show each gene set separately. (**c**) Volcano plot showing the adjusted p-values and log fold changes of smooth-muscle cluster markers (**Fig. 1b, e**) that were detected in bulk RNA-seq of *E*13.5 Myocd-KO lungs compared to controls. The percentages of genes in each quadrant of the volcano plot are indicated. (**d**) Adjusted p-values plotted against the mean of regularized log-transformed counts across all samples.

Supplementary Tables

Supplementary Table 1. Markers for clusters of embryonic lung cells identified in Fig. 1.

Supplementary Table 2. Genes that are differentially expressed in either sub-epithelial or sub-mesothelial mesenchymal cells relative to each other.

Supplementary Table 3. Curated list of genes from the MGI database that are expressed in the embryonic pulmonary mesenchyme.

Supplementary Table 4. GO enrichment analysis results for genes that are differentially expressed in either sub-epithelial or sub-mesothelial mesenchymal cells relative to each other.

Supplementary Table 5. Gene sets identified in the diffusion analysis of smooth muscle differentiation in Fig. 5.

Supplementary Table 6. KEGG pathway enrichment analysis results for gene sets identified in the diffusion analysis of smooth muscle differentiation in Fig. 5.

Supplementary Videos

Supplementary Video 1. Time-lapse imaging of lungs isolated from a Dermo1-Cre/+;Confetti/+ embryo at *E*11.5.

Figure 1

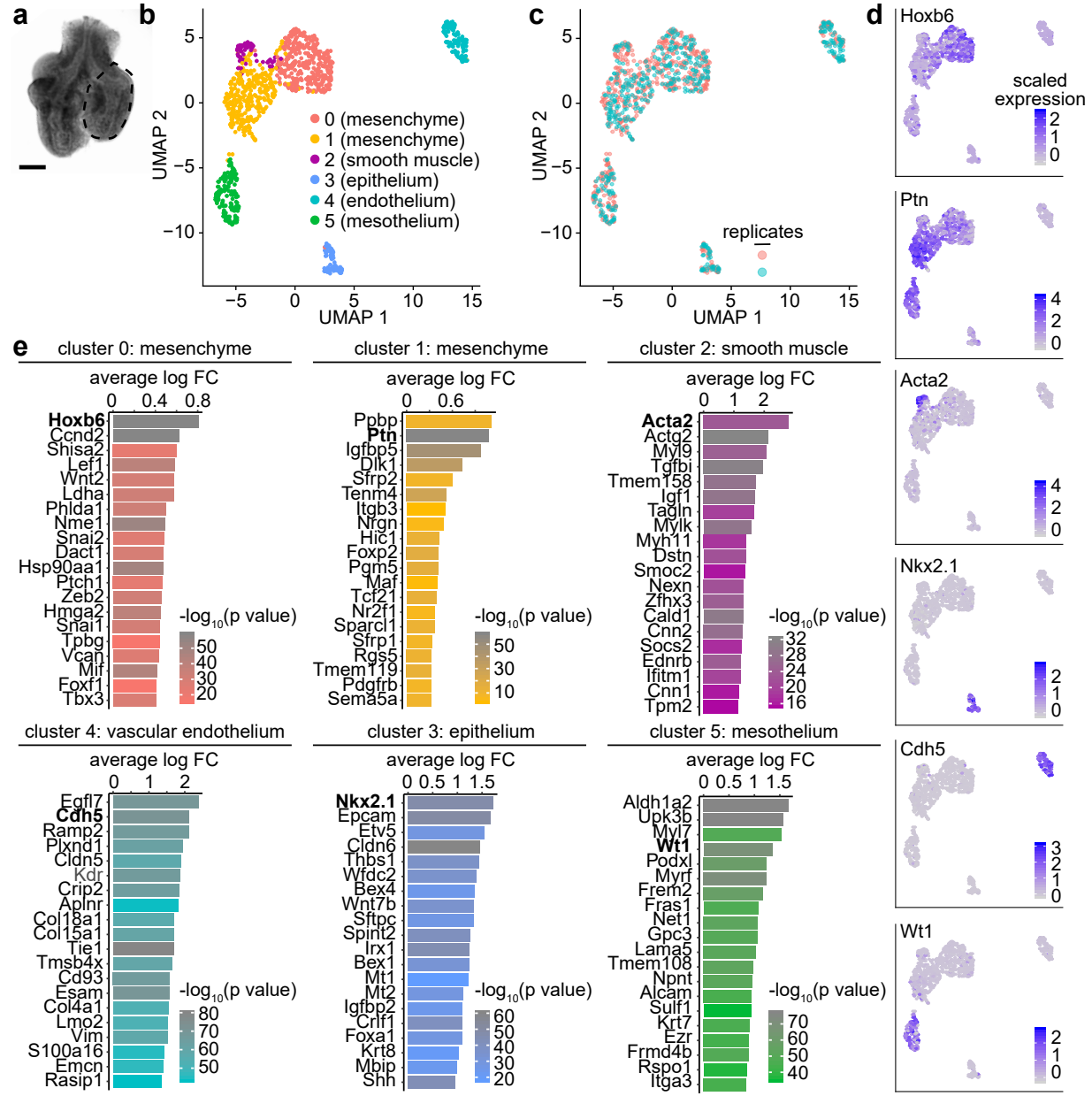

a
b
UMAP 2
UMAP 1
0 (mesenchyme)
1 (mesenchyme)
2 (smooth muscle)
3 (epithelium)
4 (endothelium)
5 (mesothelium)
c
replicates
d
Hoxb6
scaled expression
Ptn
Acta2
Nkx2.1
Cdh5
Wt1
e
cluster 0: mesenchyme
Hoxb6 Ccnd2 Shisa2 Lef1 Wnt2 Ldha Phlda1 Nme1 Snai2 Dact1 Hsp90aa1 Ptch1 Zeb2 Hmga2 Snai1 Tpbg Vcan Mif Foxf1 Tbx3
cluster 1: mesenchyme
Ppbp Ptn Igfbp5 Dlk1 Sfrp2 Tenm4 Itgb3 Nrgn Hic1 Foxp2 Pgm5 Maf Tcf21 Nr2f1 Sparcl1 Sfrp1 Rgs5 Tmem119 Pdgfrb Sema5a
cluster 2: smooth muscle
Acta2 Actg2 Myl9 Tgfbi Tmem158 Igf1 Tagln Mylk Myh11 Dstn Smoc2 Nexn Zfhx3 Cald1 Cnn2 Socs2 Ednrb Ifitm1 Cnn1 Tpm2
cluster 4: vascular endothelium
Egfl7 Cdh5 Ramp2 Plxnd1 Cldn5 Kdr Crip2 Aplnr Col18a1 Col15a1 Tie1 Tmsb4x Cd93 Esam Col4a1 Lmo2 Vim S100a16 Emcn Rasip1
cluster 3: epithelium
Nkx2.1 Epcam Etv5 Cldn6 Thbs1 Wfdc2 Bex4 Wnt7b Sftpc Spint2 Irx1 Bex1 Mt1 Mt2 Igfbp2 Crlf1 Foxa1 Krt8 Mbip Shh
cluster 5: mesothelium
Aldh1a2 Upk3b Myl7 Wt1 Podxl Myrf Frem2 Fras1 Net1 Gpc3 Lama5 Tmem108 Npnt Alcam Sulf1 Krt7 Ezr Frmd4b Rspo1 Itga3
average log FC
-log10(p value)

Figure 2

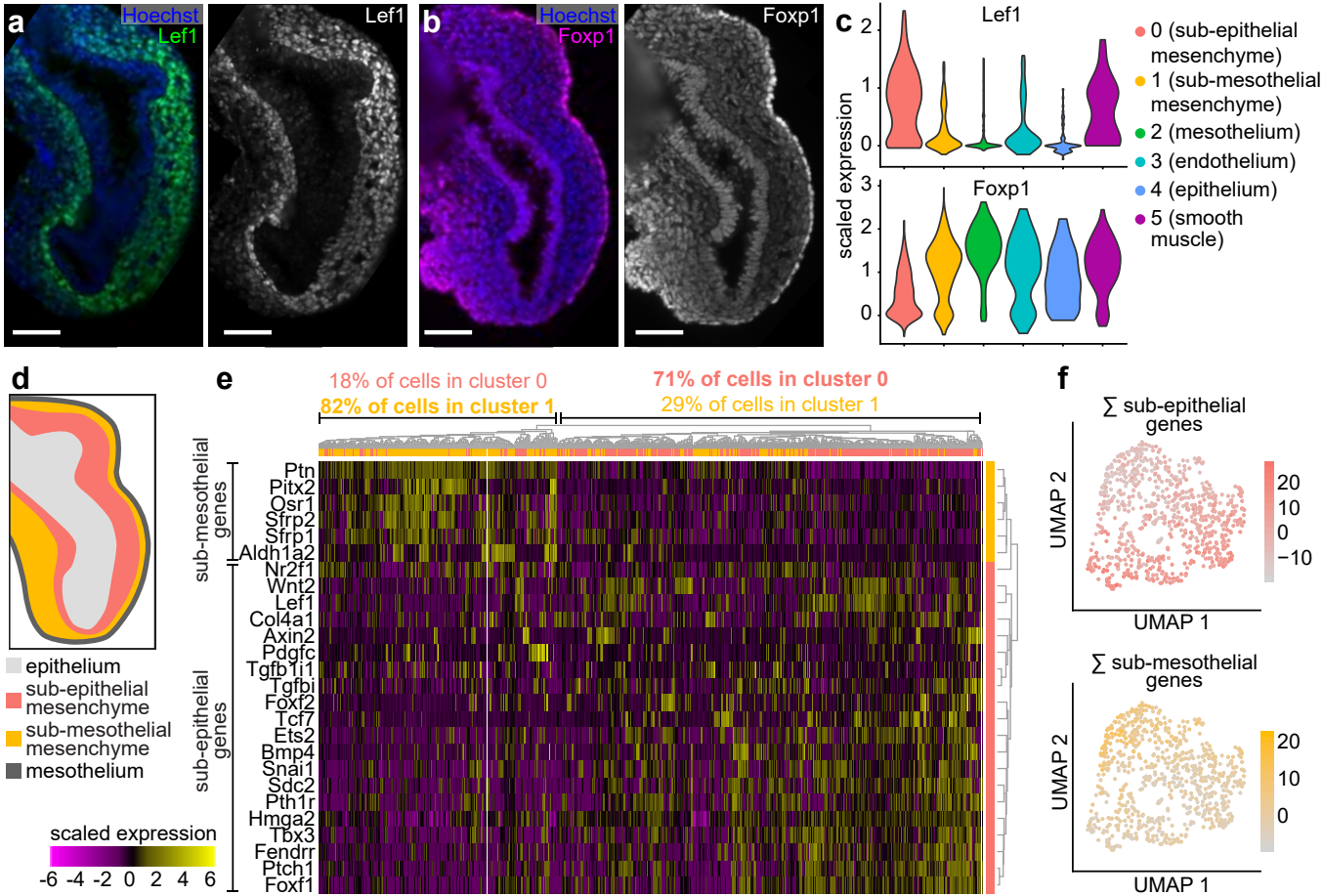
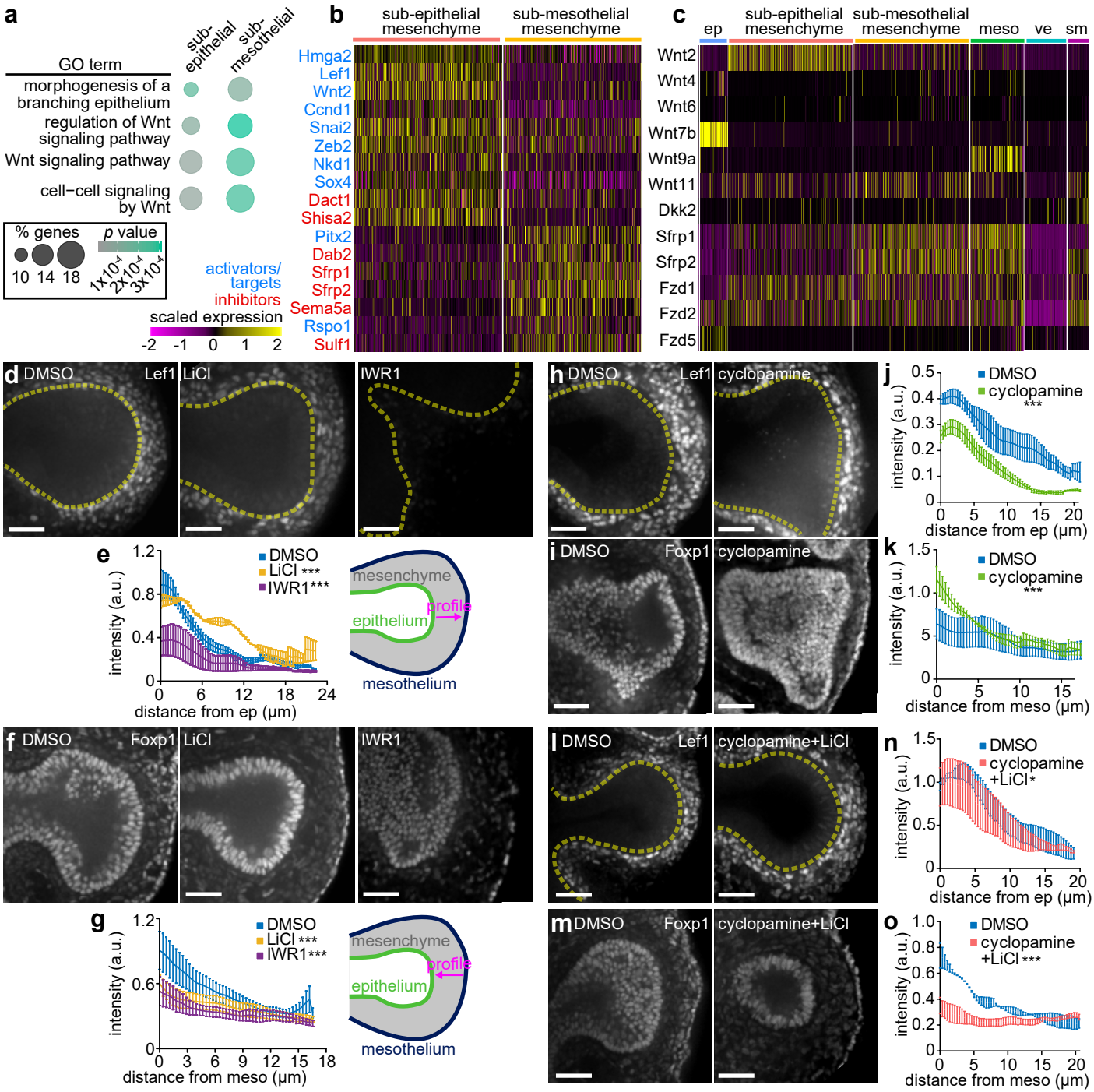

a
Hoechst
Lef1
Lef1
b
Hoechst
Foxp1
Foxp1
c
Lef1
Foxp1
scaled expression
0 (sub-epithelial mesenchyme)
1 (sub-mesothelial mesenchyme)
2 (mesothelium)
3 (endothelium)
4 (epithelium)
5 (smooth muscle)
d
epithelium
sub-epithelial mesenchyme
sub-mesothelial mesenchyme
mesothelium
scaled expression
-6 -4 -2 0 2 4 6
e
18% of cells in cluster 0
82% of cells in cluster 1
71% of cells in cluster 0
29% of cells in cluster 1
sub-mesothelial genes
sub-epithelial genes
Ptn
Pitx2
Qsr1
Sfrp2
Sfrp1
Aldh1a2
Nr2f1
Wnt2
Lef1
Col4a1
Axin2
Pdgfc
Tgfb1i1
Tgfbi
Foxf2
Tcf7
Ets2
Bmp4
Snai1
Sdc2
Pth1r
Hmga2
Tbx3
Fendrr
Ptch1
Foxf1
f
∑ sub-epithelial genes
UMAP 2
UMAP 1
∑ sub-mesothelial genes
UMAP 2
UMAP 1

Figure 3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GO term
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sub-mesothelial
morphogenesis of a branching epithelium
regulation of Wnt signaling pathway
Wnt signaling pathway
cell−cell signaling by Wnt
% genes
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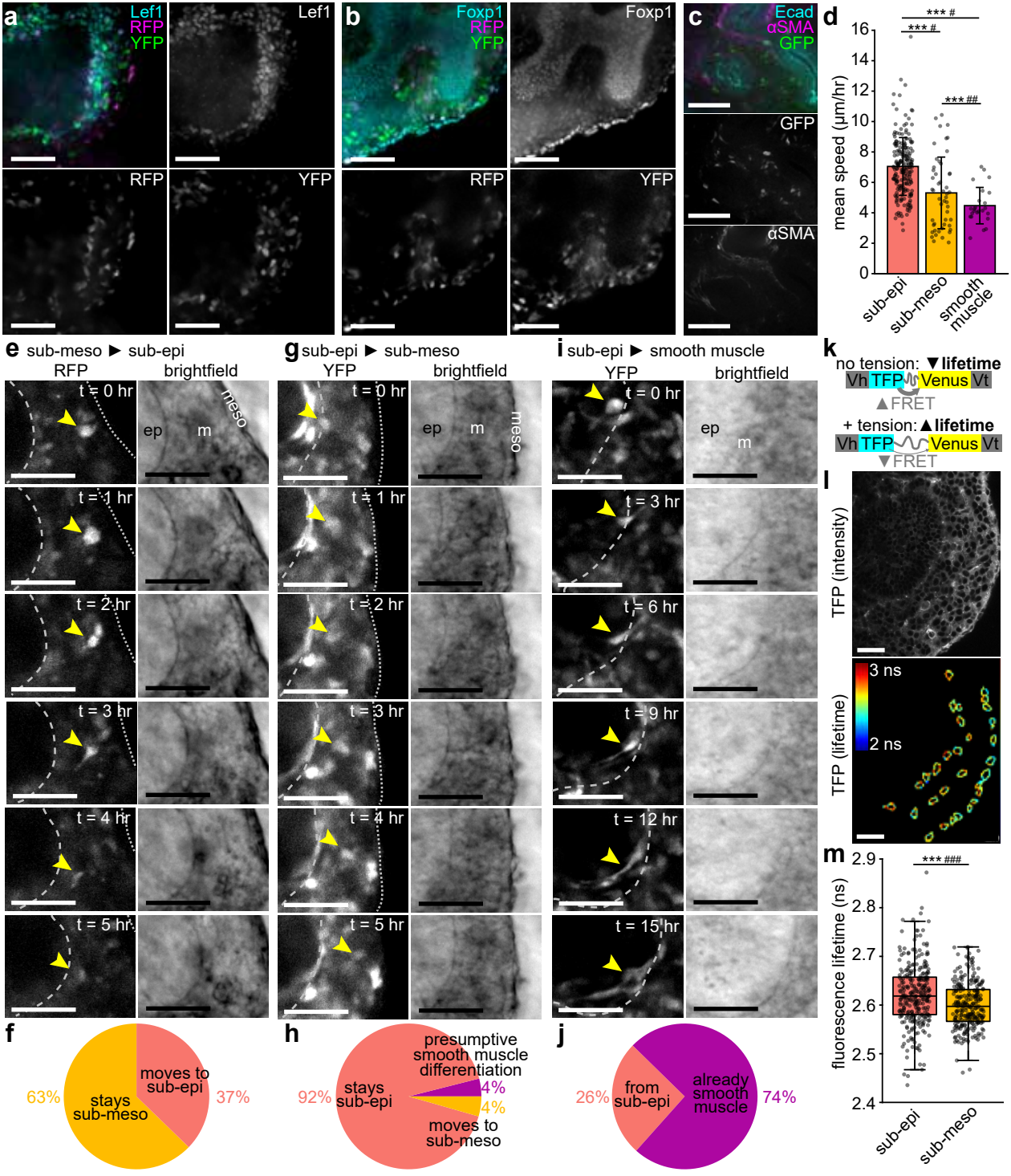
p value
1x10-4
2x10-4
3x10-4
b
sub-epithelial mesenchyme
sub-mesothelial mesenchyme
Hmga2
Lef1
Wnt2
Ccnd1
Snai2
Zeb2
Nkd1
Sox4
Dact1
Shisa2
Pitx2
Dab2
Sfrp1
Sfrp2
Sema5a
Rspo1
Sulf1
activators/ targets
inhibitors
scaled expression
-2 -1 0 1 2
c
ep
sub-epithelial mesenchyme
sub-mesothelial mesenchyme
meso
ve
sm
Wnt2
Wnt4
Wnt6
Wnt7b
Wnt9a
Wnt11
Dkk2
Sfrp1
Sfrp2
Fzd1
Fzd2
Fzd5
d DMSO Lef1 LiCl IWR1
e
DMSO
LiCl ***
IWR1***
intensity (a.u.)
distance from ep (μm)
mesenchyme
epithelium
profile
mesothelium
f DMSO Foxp1 LiCl IWR1
g
DMSO
LiCl ***
IWR1***
intensity (a.u.)
distance from meso (μm)
mesenchyme
epithelium
profile
mesothelium
h DMSO Lef1 cyclopamine
i DMSO Foxp1 cyclopamine
j
DMSO
cyclopamine
***
intensity (a.u.)
distance from ep (μm)
k
DMSO
cyclopamine
***
intensity (a.u.)
distance from meso (μm)
l DMSO Lef1 cyclopamine+LiCl
m DMSO Foxp1 cyclopamine+LiCl
n
DMSO
cyclopamine +LiCl*
intensity (a.u.)
distance from ep (μm)
o
DMSO
cyclopamine +LiCl ***
intensity (a.u.)
distance from meso (μm)

Figure 4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RFP
YFP
Lef1
RFP
YFP
b
Foxp1
RFP
YFP
Foxp1
RFP
YFP
c
Ecad
αSMA
GFP
GFP
αSMA
d
mean speed (μm/hr)
*** #
*** #
*** ##
sub-epi
sub-meso
smooth muscle
e sub-meso ▶ sub-epi
RFP
brightfield
t = 0 hr
t = 1 hr
t = 2 hr
t = 3 hr
t = 4 hr
t = 5 hr
ep
m
meso
g sub-epi ▶ sub-meso
YFP
brightfield
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ep
m
meso
i sub-epi ▶ smooth muscle
YFP
brightfield
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t = 3 hr
t = 6 hr
t = 9 hr
t = 12 hr
t = 15 hr
ep
m
k
no tension: ▼lifetime
Vh TFP Venus Vt
▲FRET
+ tension: ▲lifetime
Vh TFP Venus Vt
▼FRET
l
TFP (intensity)
TFP (lifetime)
3 ns
2 ns
m
fluorescence lifetime (ns)
*** ###
sub-epi
sub-meso
f
63%
stays sub-meso
moves to sub-epi
37%
h
92%
stays sub-epi
presumptive smooth muscle differentiation
4%
4%
moves to sub-meso
j
26%
from sub-epi
already smooth muscle
74%

Figure 5

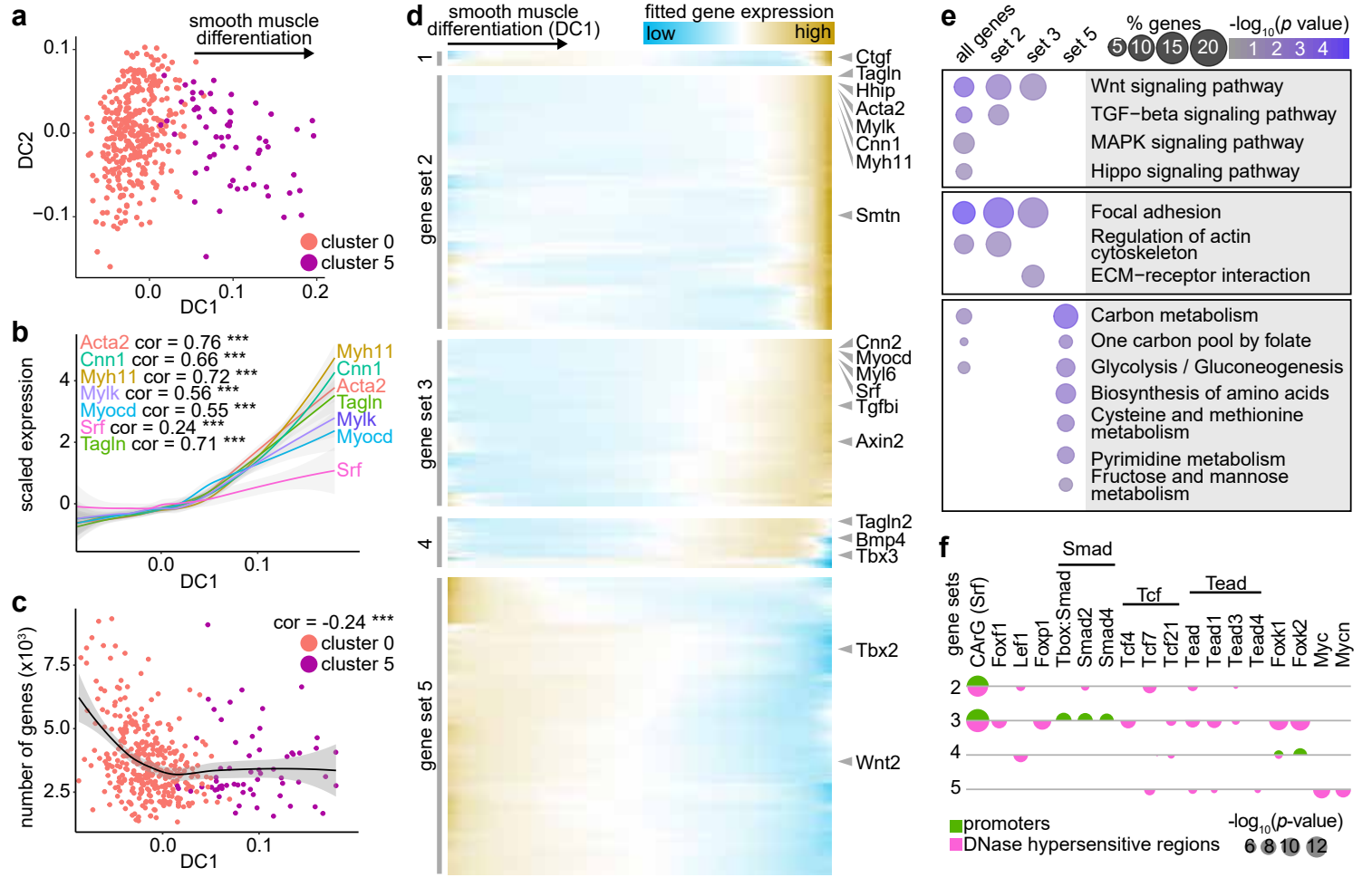

a
smooth muscle differentiation
DC2
DC1
cluster 0
cluster 5
b
Acta2 cor = 0.76 ***
Cnn1 cor = 0.66 ***
Myh11 cor = 0.72 ***
Mylk cor = 0.56 ***
Myocd cor = 0.55 ***
Srf cor = 0.24 ***
Tagln cor = 0.71 ***
scaled expression
DC1
c
cor = -0.24 ***
cluster 0
cluster 5
number of genes (x10³)
DC1
d
smooth muscle differentiation (DC1)
fitted gene expression
low
high
gene set 2
gene set 3
gene set 5
Ctgf
Tagln
Hhip
Acta2
Mylk
Cnn1
Myh11
Smtn
Cnn2
Myocd
Myl6
Srf
Tgfbi
Axin2
Tagln2
Bmp4
Tbx3
Tbx2
Wnt2
e
all genes
set 2
set 3
set 5
% genes
-log10(p value)
Wnt signaling pathway
TGF−beta signaling pathway
MAPK signaling pathway
Hippo signaling pathway
Focal adhesion
Regulation of actin cytoskeleton
ECM−receptor interaction
Carbon metabolism
One carbon pool by folate
Glycolysis / Gluconeogenesis
Biosynthesis of amino acids
Cysteine and methionine metabolism
Pyrimidine metabolism
Fructose and mannose metabolism
f
Smad
Tcf
Tead
gene sets
CArG (Srf)
Foxf1
Lef1
Foxp1
Tbox:Smad
Smad2
Smad4
Tcf4
Tcf7
Tcf21
Tead
Tead1
Tead3
Tead4
Foxk1
Foxk2
Myc
Mycn
promoters
DNase hypersensitive regions
-log10(p-value)

Figure 6

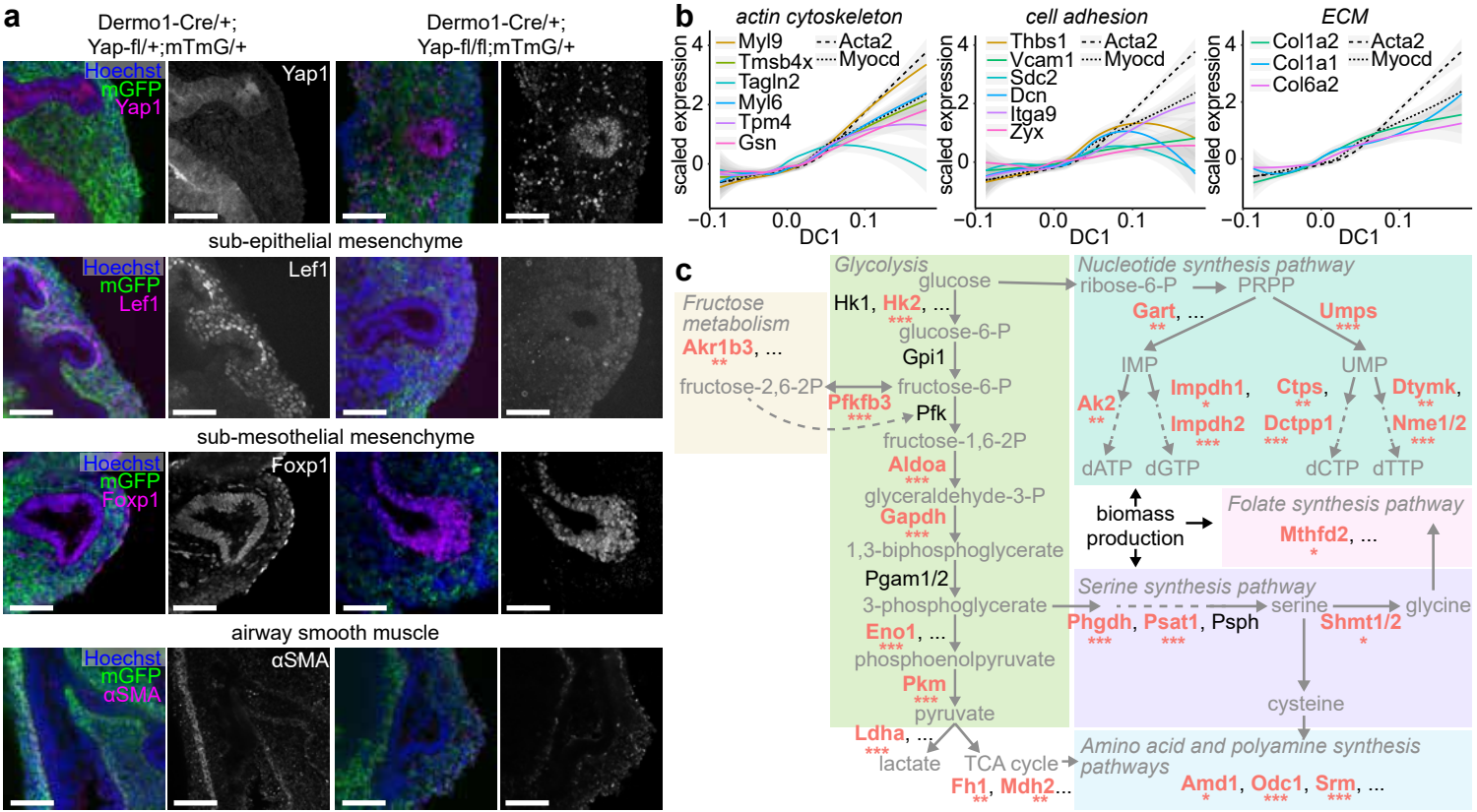
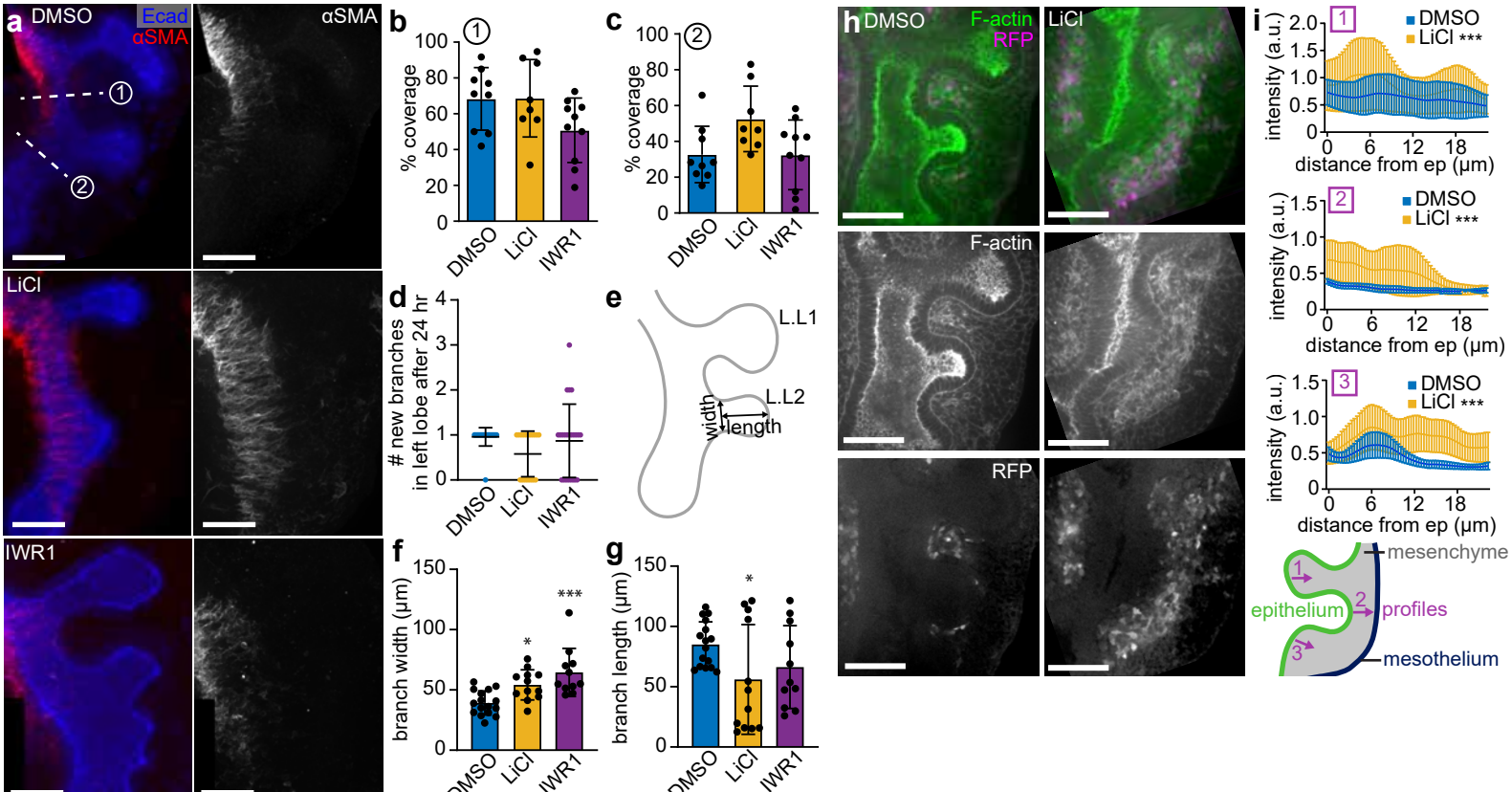
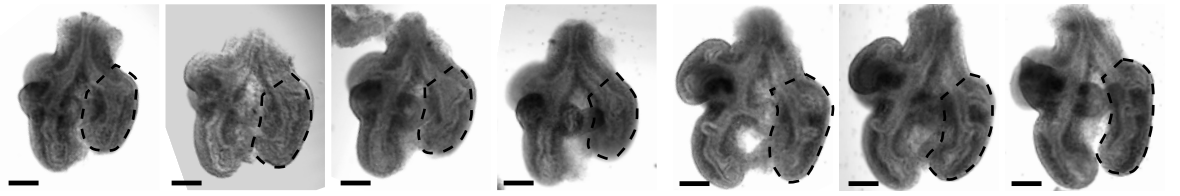

a
Dermo1-Cre/+; Yap-fl/+;mTmG/+
Dermo1-Cre/+; Yap-fl/fl;mTmG/+
Hoechst
mGFP
Yap1
Lef1
Foxp1
αSMA
sub-epithelial mesenchyme
sub-mesothelial mesenchyme
airway smooth muscle
b
actin cytoskeleton
cell adhesion
ECM
Myl9
Tmsb4x
Tagln2
Myl6
Tpm4
Gsn
Acta2
Myocd
Thbs1
Vcam1
Sdc2
Dcn
Itga9
Zyx
Col1a2
Col1a1
Col6a2
scaled expression
DC1
c
Glycolysis
Fructose metabolism
Nucleotide synthesis pathway
Folate synthesis pathway
Serine synthesis pathway
Amino acid and polyamine synthesis pathways
glucose
Hk1, Hk2, ...
glucose-6-P
Gpi1
fructose-6-P
fructose-2,6-2P
Pfkfb3
Pfk
fructose-1,6-2P
Aldoa
glyceraldehyde-3-P
Gapdh
1,3-biphosphoglycerate
Pgam1/2
3-phosphoglycerate
Eno1, ...
phosphoenolpyruvate
Pkm
pyruvate
Ldha, ...
lactate
TCA cycle
Fh1, Mdh2...
Akr1b3, ...
ribose-6-P
PRPP
Gart, ...
Umps
IMP
UMP
Ak2
Impdh1,
Impdh2
Ctps,
Dctpp1
Dtymk,
Nme1/2
dATP
dGTP
dCTP
dTTP
biomass production
Mthfd2, ...
Phgdh, Psat1, Psph
serine
glycine
Shmt1/2
cysteine
Amd1, Odc1, Srm, ...

Figure 7


a
DMSO
Ecad
αSMA
αSMA
LiCl
IWR1
b
% coverage
DMSO
LiCl
IWR1
c
% coverage
DMSO
LiCl
IWR1
d
new branches in left lobe after 24 hr
DMSO
LiCl
IWR1
e
L.L1
L.L2
width
length
f
branch width (μm)
DMSO
LiCl
IWR1
g
branch length (μm)
DMSO
LiCl
IWR1
h
DMSO
F-actin
RFP
LiCl
F-actin
RFP
i
intensity (a.u.)
distance from ep (μm)
DMSO
LiCl ***
mesenchyme
epithelium
profiles
mesothelium

Supplementary Figure 1

a

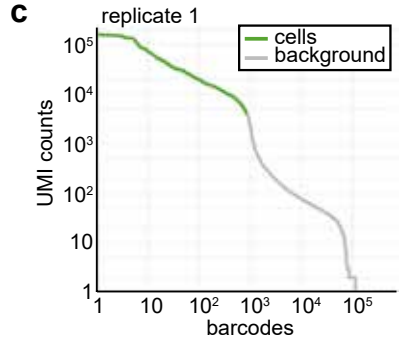


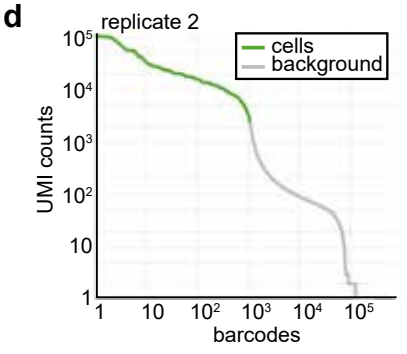
b

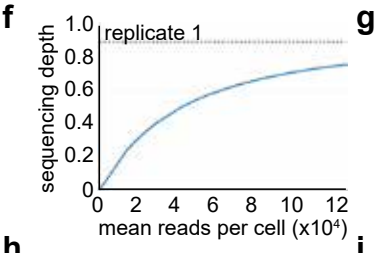
General	1	2
Estimated number of cells	889	1082
Mean reads per cell	142396	119861
Median genes per cell	2779	1592
Fraction of reads in cells	71.50%	65.10%
Total genes detected	17529	17017
Median UMI counts per cell	9026	7713

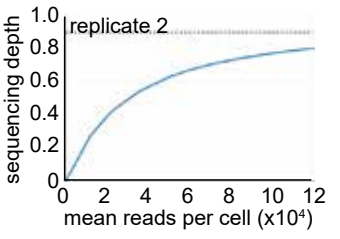
e

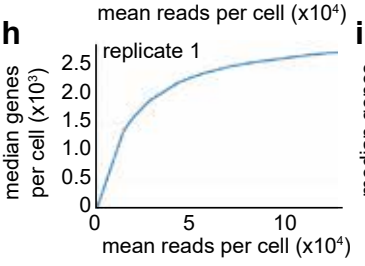
Sequencing	1	2
Number of reads	1E+08	1E+08
Valid barcodes	97.80%	97.90%
Sequencing saturation	78.10%	80.30%
Q30 bases in barcode	97.90%	97.90%
Q30 bases in RNA read	86.90%	86.20%
Q30 bases in UMI	98%	98.10%

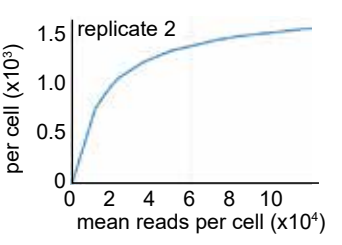






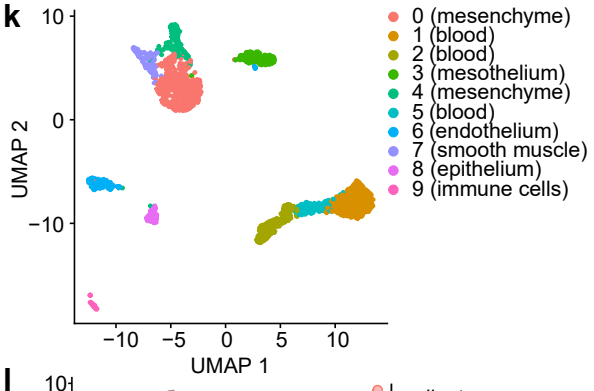


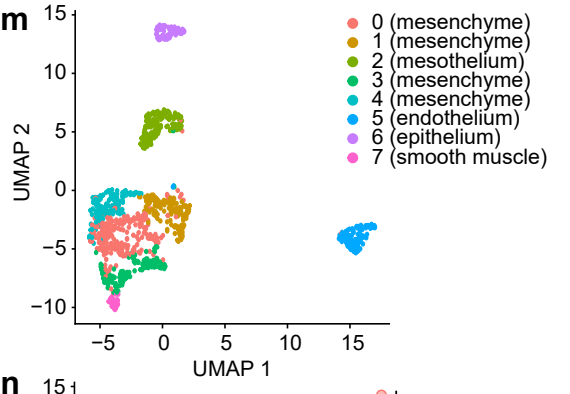


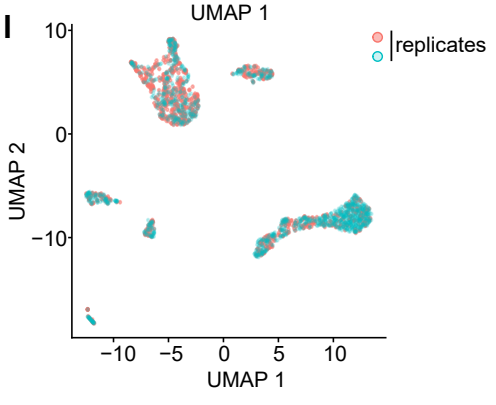


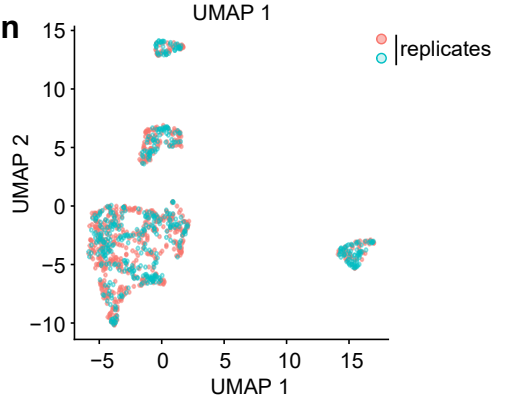
j

Mapping	1	2
Reads mapped confidently to genome	73.30%	72.10%
Reads mapped confidently to intergenic regions	5.00%	4.40%
Reads mapped confidently to intronic regions	9.40%	7.10%
Reads mapped confidently to exonic regions	58.90%	60.70%
Reads mapped confidently to transcriptome	57.20%	59.30%
Reads mapped antisense to gene	0.80%	0.60%

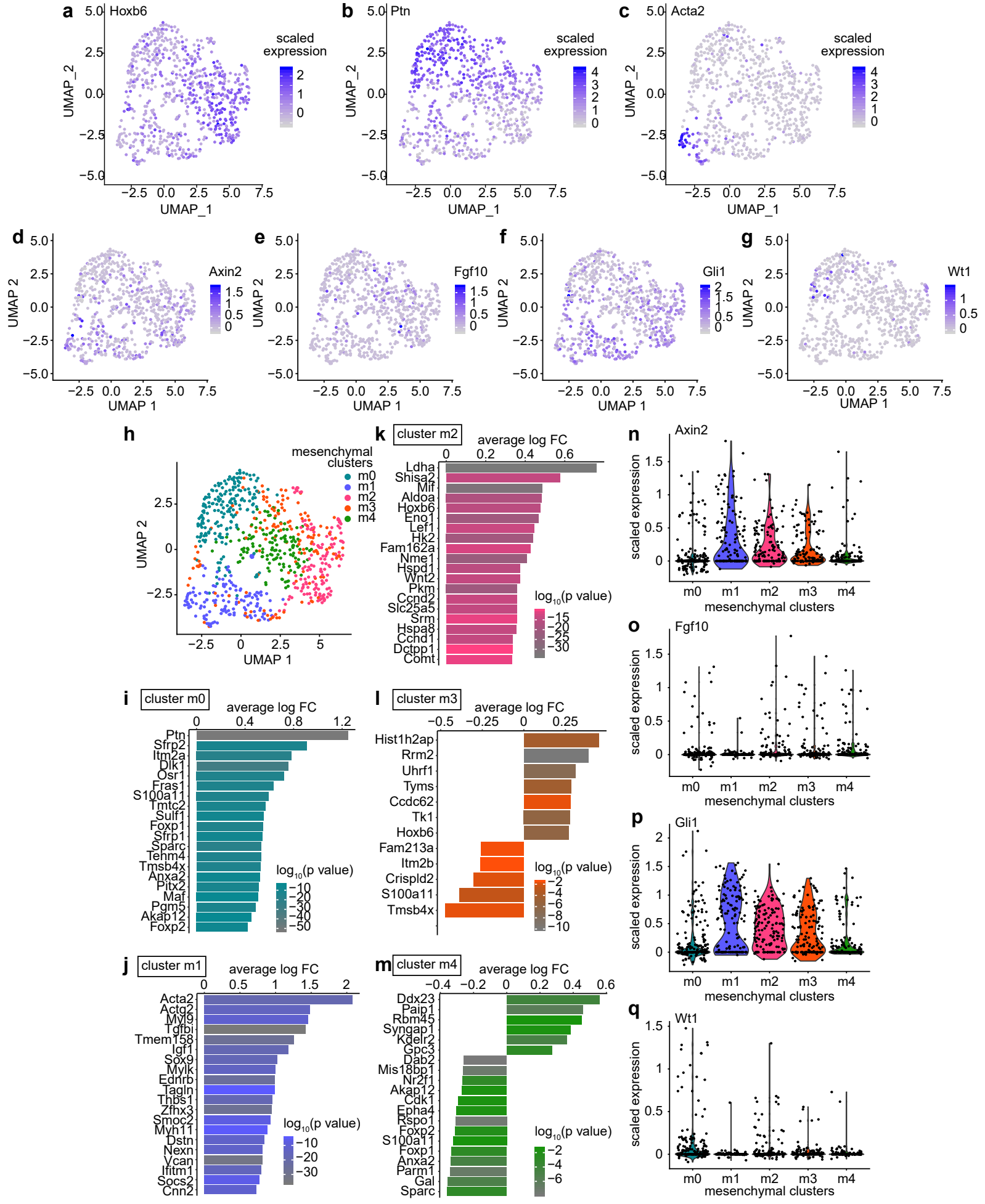




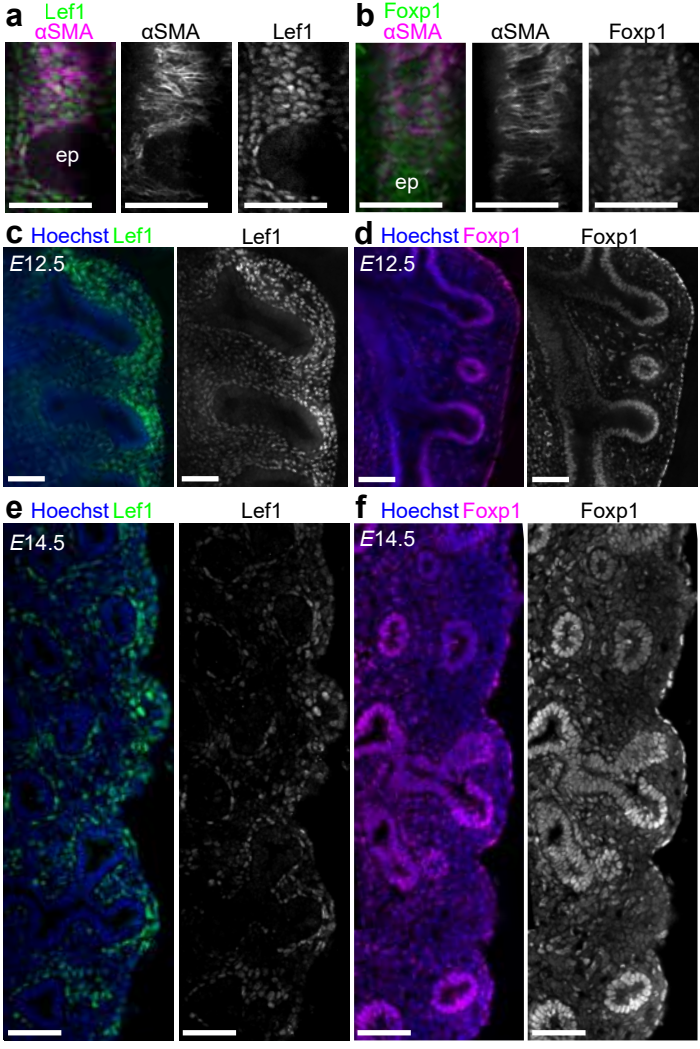




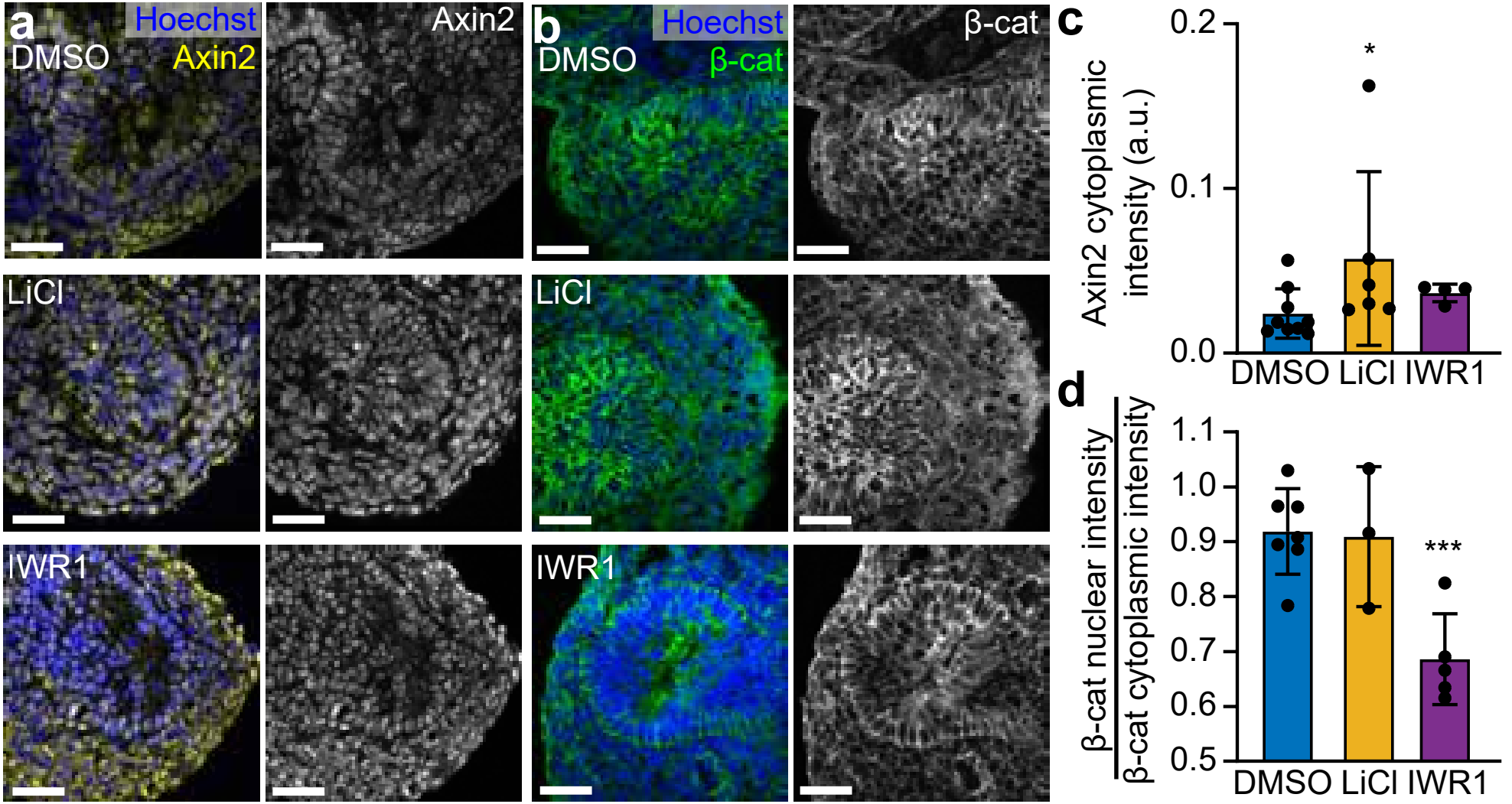
Supplementary Figure 2



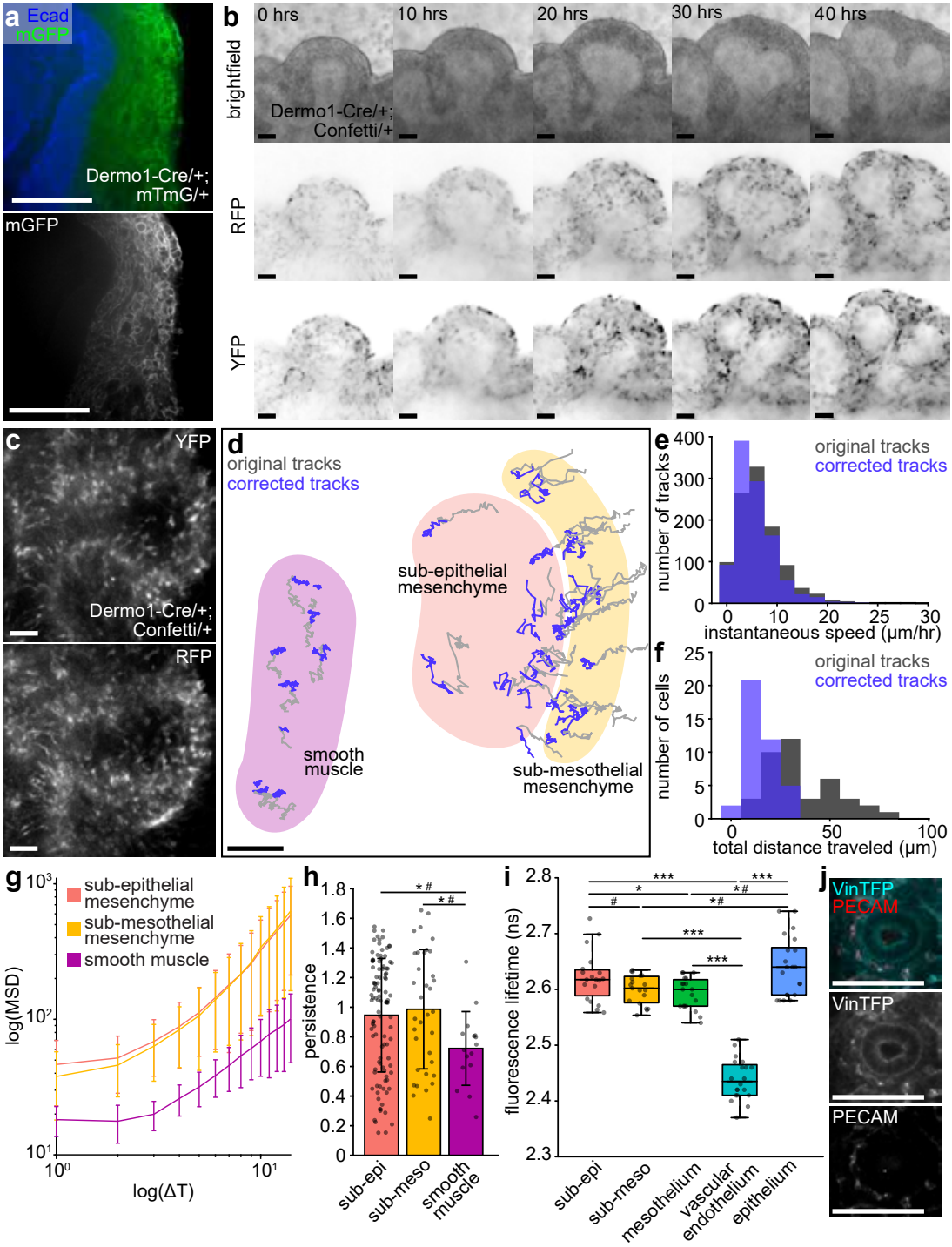
Supplementary Figure 3



Supplementary Figure 4



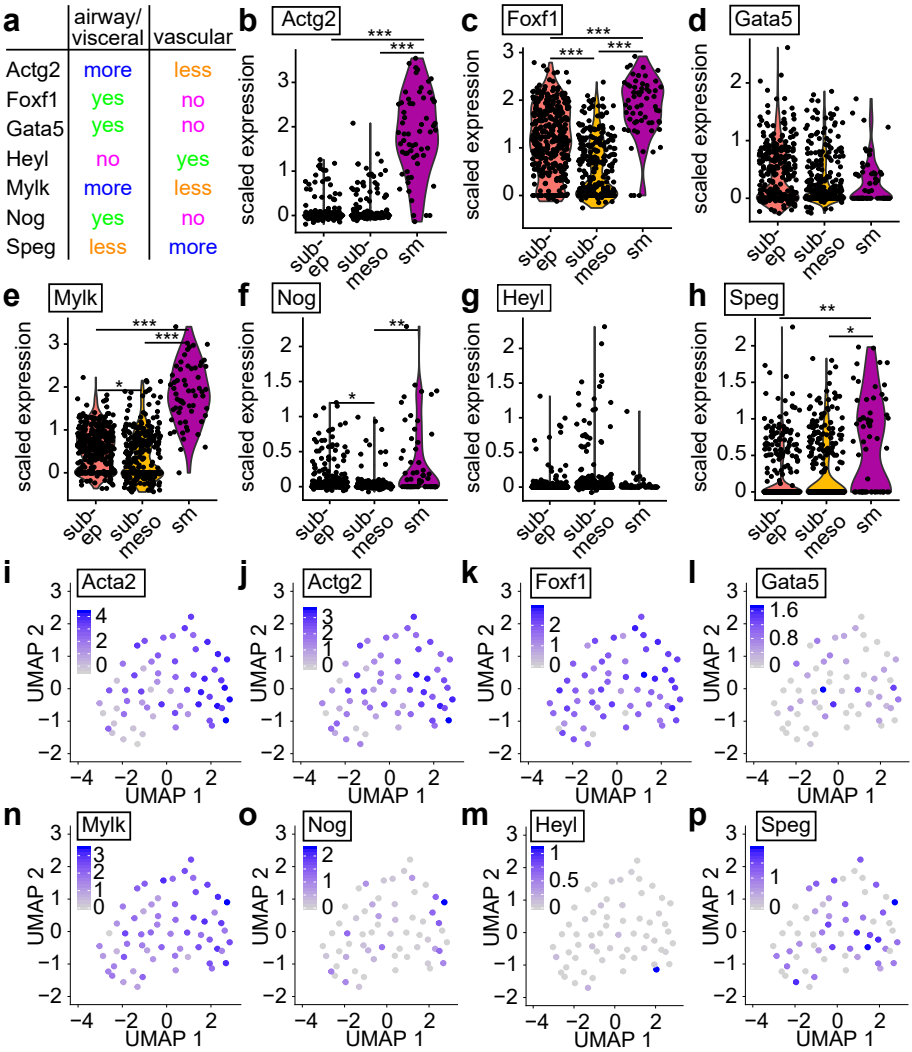
Supplementary Figure 5

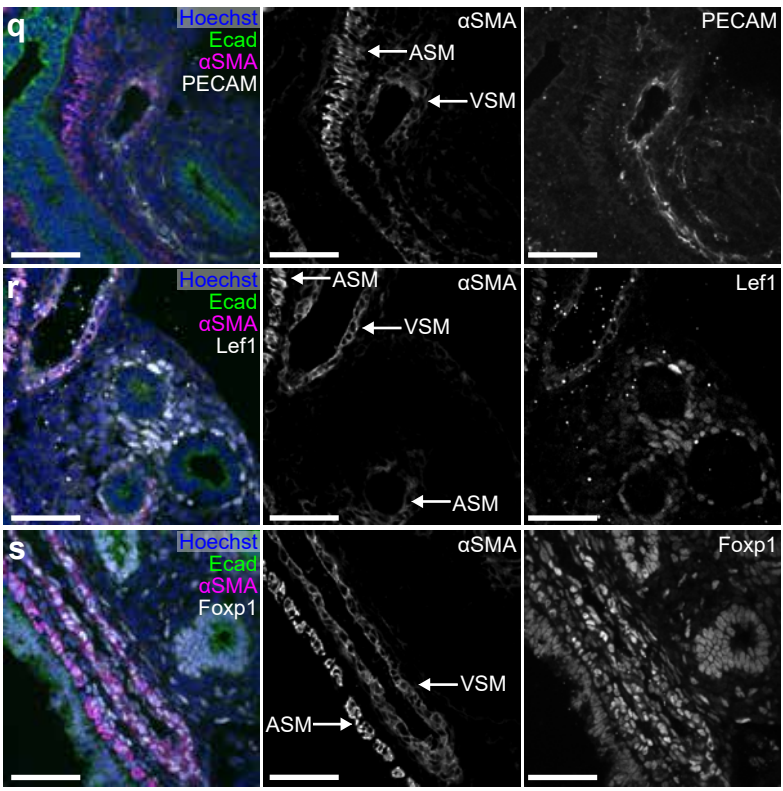


Supplementary Figure 6

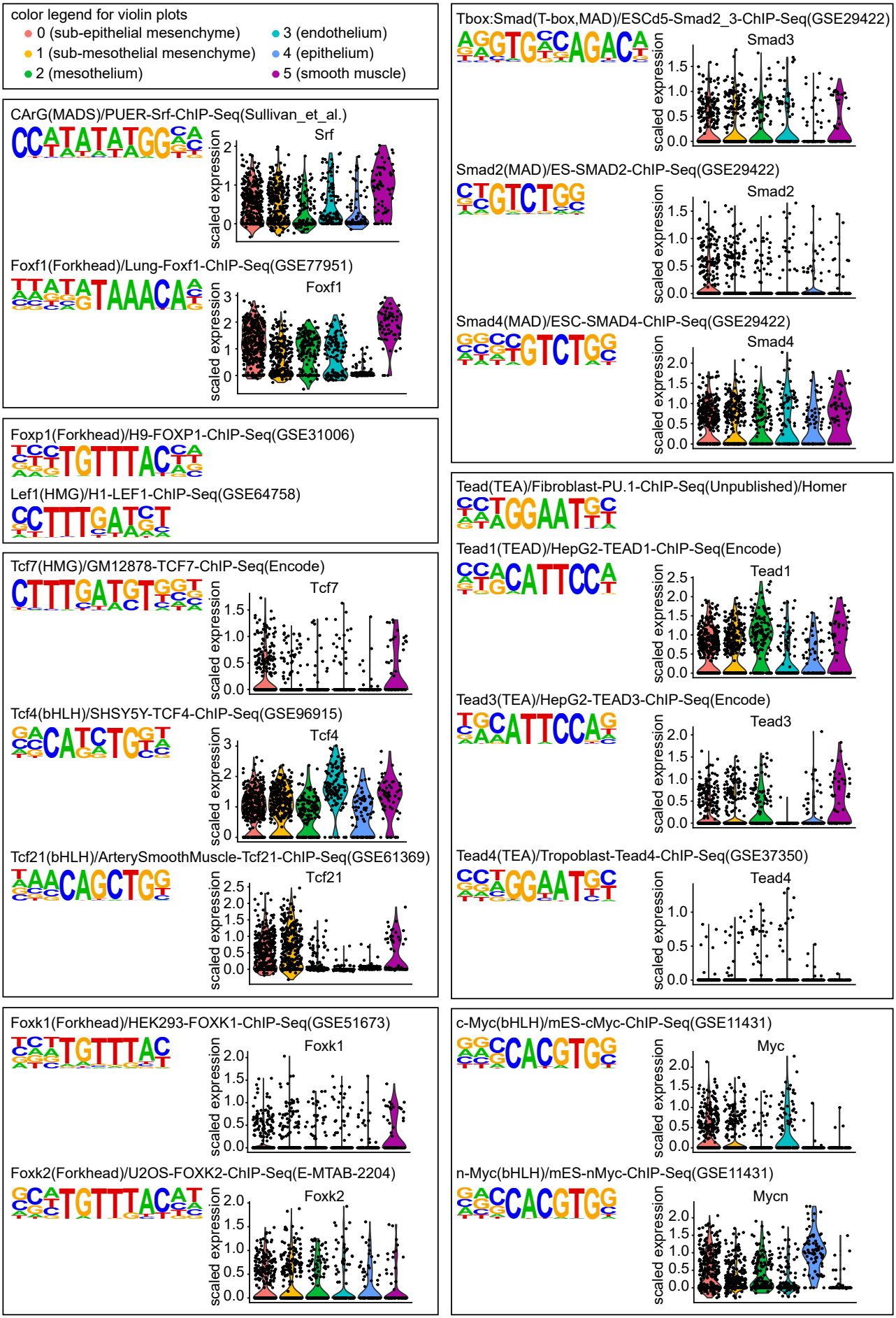
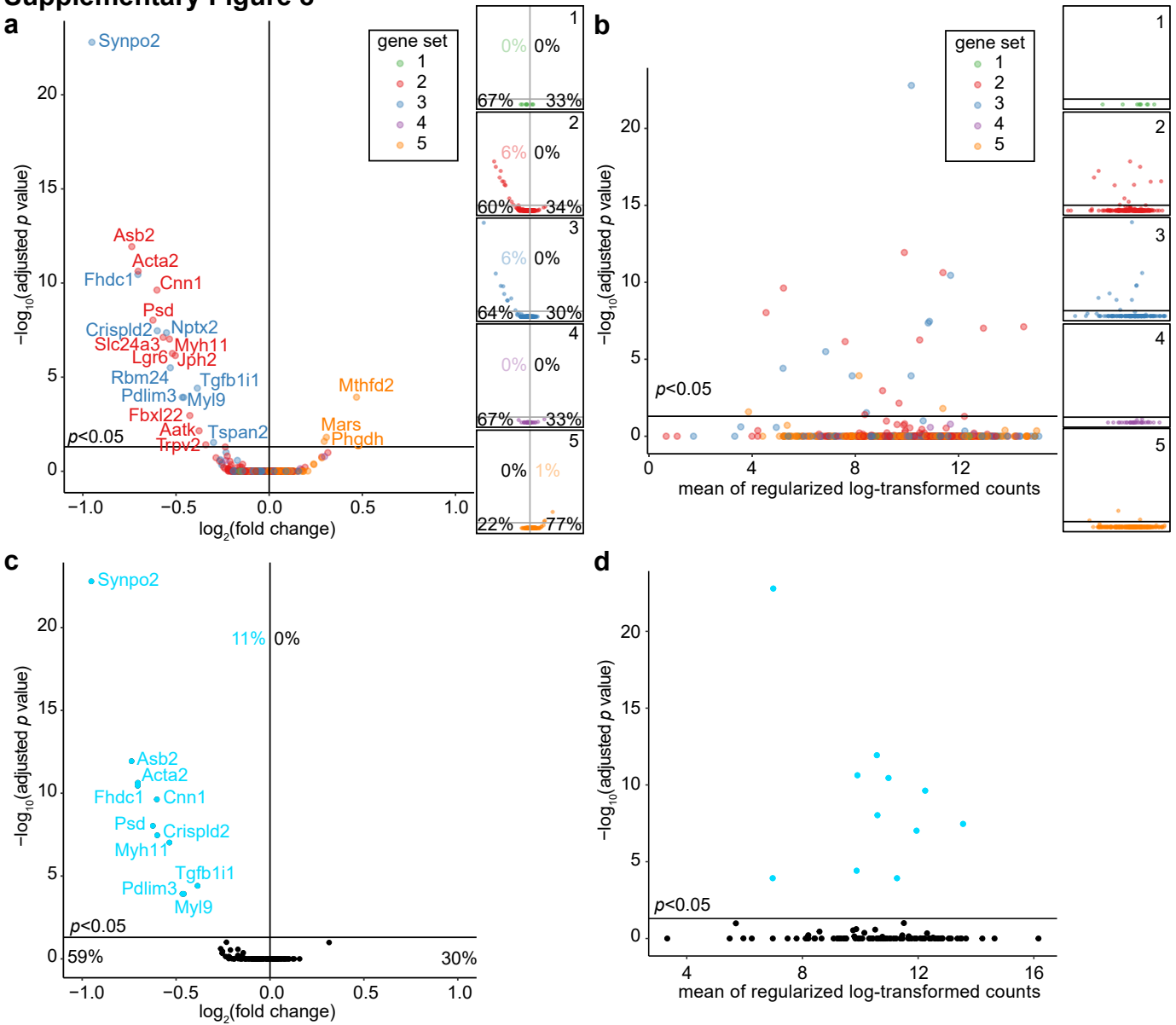
a

	airway/ visceral	vascular
Actg2	more	less
Foxf1	yes	no
Gata5	yes	no
Heyl	no	yes
Mylk	more	less
Nog	yes	no
Speg	less	more





Supplementary Figure 7



Supplementary Figure 8