Transplantable human thyroid organoids generated from embryonic stem cells to rescue hypothyroidism

Mírian Romitti [1], Barbara de Faria da Fonseca [1], Gilles Doumont [2], Pierre Gillotay [1], Adrien Tourneur [1], Sema Elif Eski [1], Gaetan Van Simaeys [2,3], Laura Chomette [1], Helene Lasolle [1], Olivier Monestier [1], Dominika Figini Kasprzyk [1], Vincent Detours [1], Sumeet Pal Singh [1], Serge Goldman [2,3], Samuel Refetoff [4] and Sabine Costagliola [1]

[1] Institut de Recherche Interdisciplinaire en Biologie Humaine et Moléculaire (IRIBHM), Université Libre de Bruxelles (ULB), Brussels, Belgium

[2] Center for Microscopy and Molecular Imaging (CMMI), Université libre de Bruxelles (ULB), Charleroi (Gosselies), Belgium

[3] Service de Médecine Nucléaire, Hôpital Érasme, Université libre de Bruxelles (ULB), Brussels, Belgium

[4] Departments of Medicine, Pediatrics and Committee on Genetics, The University of Chicago, Chicago, IL, USA

The function of the thyroid gland is to capture iodide in order to synthesize hormones that act on almost all tissues and are essential for normal growth and metabolism. Low plasma levels of thyroid hormones lead to hypothyroidism, which is one of the most common disorder in humans which is not always satisfactorily treated by lifelong hormone replacement. Therefore, in addition to the lack of *in vitro* tractable models to study human thyroid development, differentiation and maturation, there is a need for new therapeutic approaches that involve replacement of thyroid tissue responsive to changing demands for thyroid hormone. Here we report the first transplantable thyroid

organoids derived from human embryonic stem cells capable of restoring plasma thyroid hormone to athyreotic mice as a proof of concept for future therapeutic development.

Hypothyroidism is a very common disorder with a prevalence of 1% to 5% worldwide. It results from insufficient thyroid hormone (TH) production due to autoimmune damage to the thyroid gland, iodide excess or deficiency, external irradiation, genetic defects or other defects manifesting at birth (congenital hypothyroidism, CH) and surgical or radioactive thyroid ablation to treat hyperthyroidism or thyroid cancer [1–3]. Despite well-established TH replacement therapy, it is estimated that up to one-third of patients do not receive an adequate treatment [4,5] while a large proportion have impaired health-related quality of life, particularly psychological well-being [6,7]. In addition, studies have shown that children with CH can develop motor, cognitive, and social dysfunction even when diagnosed through newborn screening followed by early institution of TH replacement [7,8]. Indeed, constant exogenous supply of TH does not provide for changes in TH requirement associated with growth, puberty, pregnancy and stress, leaving room for new therapeutic approaches, such as regenerative medicine, that would accommodate the variation in TH demand.

In recent years, significant progress has been made in the development and application of human cell-based models for the study of human biology and disease modeling. Human embryonic stem cell (ESC)-based protocols have been developed and led to the generation of several types of human organoids that include brain, intestine, stomach, liver, kidney, lung, endometrium, prostate, pancreas, and retina [8,9]. With regard to the thyroid, murine ESC-derived organoids have been shown to recapitulate *in vitro* the developmental stages of the thyroid gland with the ability to produce TH *in vitro* and *in vivo* after transplantation to mice with ablated thyroid glands [11–15].

In contrast, human thyroid cells so far generated from stem cells have not shown full maturation *in vitro* and ability to compensate for low TH levels when transplanted into animals devoid of thyroid tissue [10–14]. These difficulties in producing functional human thyroid follicles capable of restoring thyroid function *in vivo* have been partially overcome by using organoids generated from suspensions of adult human thyroid cells, but with some limitations. Hence, Coppes et al. [15] generated thyrospheres from human thyroid glands, but 26 weeks are required to detect human thyroid tissue when these organoids are transplanted into hypothyroid mice, and plasma levels of T4 did not increase significantly [15].

Given the lack of a functional *in vitro* thyroid model to further explore various aspects related to thyroid development, maturation and disease and to provide an alternative to imperfect drug treatment to restore thyroid function in patients, there is an urgent need to define an optimized strategy to generate TH producing human follicles from stem cells. We used forward programming by transient overexpression of *NKX2-1* and *PAX8* transcription factors (TFs) and manipulation of signaling pathways in combination with stepwise transcriptomic characterization, to generate a functional human thyroid from pluripotent stem cells that recapitulates thyroid function *in vitro* and *in vivo*.

In vitro **differentiation of human thyroid cells**

hESC line generation and characterization: in recent years, mouse ESC-derived *in vitro* thyroid models have provided understanding of mechanisms involved in thyroid development and maturation [10,16–19]. However, replication of the protocols using hESC/iPSC was insufficient to generate a functional human thyroid *in vitro* [14,16–18]. Since we have previously shown that forward programming [20–23] by transient overexpression of the transcription factors, *Nkx2-1* and *Pax8* [24] leads to high efficiency of thyroid differentiation and functional follicle formation from mouse ESC [16], we used a similar approach to generate a recombinant human ESC line. First,

we took advantage of a previously generated NKX2-1$^{WT/GFP}$ knock-in hESC line [25] (Extended data Fig. 1a) to track thyroid differentiation and cell organization using the NKX2-1^{GFP} reporter. Furthermore, the hESC-NKX2-1$^{WT/GFP}$ line was modified to allow transient expression of *NKX2-1* and *PAX8*, by adding doxycycline (Dox; 1 mg/ml; Extended data Fig. 1b) to the culture medium (Fig. 1a). The resulting hESCs, had normal karyotype and ability to spontaneously differentiate into cells from the three germ layers (Extended data Fig. 1c-d, respectively).

Induction of thyroid status: The modified hESCs were first grown for 2 days in hanging drops to allow the formation of embryoid bodies (EBs) (Fig. 1a). The generated EBs were then cultured in matrigel drops and endoderm was induced by adding Activin A for 3 days. This treatment resulted in increased mRNA levels of the endoderm markers *SOX17* and *FOXA2* (Extended data Fig. 1e) and simultaneously improved the percentage of FOXA2 + cells, particularly in the inner compartment of EBs (Extended data Fig. 1f). After induction of the endoderm, Dox treatment promoted the overexpression of *NKX2-1* and *PAX8*. After 4 days, expression of NKX2-1 and PAX8 was detected by immunofluorescence in a large proportion of Dox-treated cells but not in the absence of Dox (Extended data Fig. 1g). Furthermore, qPCR analysis showed that not only were exogenous *NKX2-1* and *PAX8* gene expression levels significantly upregulated, but endogenous *NKX2-1*, *PAX8*, *FOXE1*, *TG*, and *TSHR* mRNA levels were also increased as early as day 9 (Extended data Fig. 1h). To determine whether forced overexpression of thyroid TFs leads to autonomous activation of endogenous cell programming in thyroid fate, Dox treatment was interrupted and cells were incubated in basal differentiation medium for 7 days (from day 9 to day 16). qPCR analysis revealed that exogenous *PAX8* expression at day 9 was similar to endogenous *PAX8* expression, but the levels of exogenous TFs decreased over time and reached control levels (+AA -Dox) from day 12. In contrast, endogenous *PAX8* levels increased dramatically and reached a plateau from

day 14 (Extended data Fig. 1i). These results suggest that Dox induction of TFs the endogenous transcriptional machinery is activated, initiating the thyroid differentiation program.

Thyroid cell population expansion and early differentiation were promoted by incubation with 8-br-cAMP for 2 weeks (from day 16 to day 30). Flow cytometry analysis confirmed growth of the thyroid population resulting in approximately 25% of total cells expressing NKX2-1^{GFP} at day 30 (Fig. 1b), reflecting the increase in proliferation as around 90% of NKX2-1^{GFP+} cells continuously expressed KI67 during the treatment period (Extended data Fig. 2a). Accordingly, transcriptomics analysis performed in NKX2-1^{GFP} cells showed high levels of various proliferation markers (Extended data Fig. 2b). In parallel, an increase in expression of early thyroid markers was also observed over time (+AA +Dox +cAMP), confirming the role of cAMP in cell differentiation (Fig. 1c). This was accompanied by a steady expression of key genes such as *NKX2-1*, *TG*, and *TSHR* from day 23 (Extended data Fig. 2c). However, key maturation markers, such as *NIS*, *TPO* and *DUOX* family, were not significantly induced by cAMP, suggesting that it is not sufficient to promote thyroid maturation and function. By tracking NKX2-1^{GFP+} cells we observed at day 28, that thyroid cells start to form follicle-like structures and immunostaining shows marked expression of *TG* and *PAX8*. Though, the cells were not organized in single-layered follicles, but a luminal compartment was observed (Extended data Fig. 2d), suggesting that the process of folliculogenesis is not yet complete at this stage.

Thyroid maturation and function: since cAMP treatment was not able to fully promote thyroid maturation despite significant expression of *TSHR*, we explored additional ways to promote thyroid differentiation. As the TSHR controls more than the Gs regulatory cascade [26], we first replaced cAMP with hrTSH from day 30. Second, we added dexamethasone (from day 30) and the TGFβ inhibitor SB431542 (from day 37), based on transcriptomic data showing substantial levels of TGFβ pathway markers (Extended data Fig. 2f) among NKX2-1 cells, and the known

inhibition of thyroid differentiation by inflammation and TGFβ pathway stimulation [27–31]. Together, these alterations of the protocol (Fig. 1a) resulted in significant improvement in the expression of key thyroid maturation markers, including *TSHR, TG, NIS /SLC5A5, TPO, DIO2,* and the *DUOX* family (Figs. 1c and Extended data Fig. 2e), while mRNA levels of TGFβ pathway effectors were reduced, particularly receptors (Extended data Fig. 2f). Subsequently, PAX8 and ZO -1 co-staining revealed monolayer-organized follicles with a well delimited lumen (Extended data Fig. 2g). On the other hand, the proportion of NKX2-1+ cells was maintained over time, whereas NKX2-1/KI67+ cells clearly decreased at day 47, compared to the early time points (Fig. 1b and Extended data Fig. 2a, respectively). Of note, our human hESC-derived protocol for thyroid generation follows the sequential events observed *in vivo*, as in human, thyroid development takes approximately 40 days from specification to folliculogenesis[32,33], a similar developmental time is required in our *in vitro* model. Considering that we artificially induce thyroid progenitor cells formation by forcing the expression of *NKX2-1* and *PAX8*, the expression of maturation genes follows the physiological sequence, with *TG* and *TSHR* being the first detected genes, followed by *TPO* and *NIS /SLC5A5* [32,33]. A similar effect trend was observed in thyroid population expansion, organization and follicle formation. However, even though the TH machinery seems to be complete, we could not detect TH-producing follicles at day 45.

Single cell characterization of human thyroid organoids.

To better characterize the resulting cell composition of our hESC-derived thyroid model, scRNA-seq analyzes were performed at day 45. Since the efficiency of the present protocol is approximately 25%, we enriched the proportion of NKX2-1^{GFP+} cells to 60%, the remaining sorted cells belonging to the GFP- population. A total of approximately 6,000 cells were used for scRNA-seq library preparation using the droplet-based assay from 10X Genomics. After

quality control (see extended data methods), we obtained 1874 cells that met all the criteria. Among those cells, we identified 7 clusters (Fig. 1d-e), including a cluster of thyroid follicular cells with 1176 cells showing expression of genes involved in development and function, including *NKX2-1*, *PAX8*, *FOXE1*, *HHEX*, *TG*, *TSHR*, and *TPO* (Fig. 1e-f). Of note, we identified three sub-clusters among the thyroid cells: Thyroid "progenitors" (477 cells) expressing mainly the thyroid TFs; immature thyrocytes (365 cells) expressing also *TG* and *TSHR*; and mature thyrocytes (334 cells) showing a canonical thyroid signature with a higher proportion of *TPO*-expressing cells (Fig. 1e-f and Extended data Fig. 3a). Furthermore, pseudotime analysis reveals a branch of differentiation originating from thyroid progenitors and moving toward immature and progressive mature thyrocytes (Fig. 1g). This transition was used to generate the trend of gene expression for the different thyroid markers along the trajectory (Fig. 1h), which follows the expected dynamics, with TFs appearing first, followed by *TSHR*, *TG*, and *TPO* expression (Fig. 1e).

The identity and molecular signature of the remaining cells was characterized, and we identified four non-thyroidal clusters: fibroblasts (146 cells) expressing *DCN*, *COL1A2*, and *PPRX1*; cardiovascular cells (182 cells) enriched in *ACTA2* and *TNNT2 markers*; airway cells (203 cells) expressing *KRT5* and *TP63* and endoderm-epithelial cells (167) expressing *FOXA1*, *FOXA2*, and *ADAM28* (Fig. 1d-e and Extended data Fig. 3b). Even if NKX2-1 also plays a critical role in lung and forebrain development [34], our protocol predominantly generates thyroid cells, since more than 75% of *NKX2-1*+ cells co-express *PAX8* and/or other thyroid markers.

Connectome: To predict possible crosstalk between thyroid cells and the other cells present in the organoids, we used CellPhone- DB, to access the ligand-receptor interaction pairs identified between thyroid clusters and other cell types. Interestingly, we found significant cell-cell interactions between thyroid cells with mainly mesodermal cells associated with several signaling pathways described as involved in thyroid development and physiology (Extended

data Fig. 3c). Previous studies performed *in vivo* and using stem cell-derived organoids have described the critical role of BMP and FGF signaling pathways in regulating thyroid specification, as well as how WNT signaling can influence thyroid development and determine lineage choice toward lung specification [10,17,19,35,36]. Here, we observed that in our multicellular organoid model, the presence of mesoderm-derived cells could be beneficial for thyroid development without supplementation of factors, as we observed that fibroblasts and cardiovascular cells are an important source of *BMP2*, *BMP4*, and *FGF2* ligands, whereas thyroid cells express the specific receptors (Extended data Fig. 3c-d). In addition, insulin-like growth factor (IGF-I) is known to support normal thyroid size and function, in part by enhancing TSH sensitivity [37]. In addition to BMP and FGF, mesodermal, airway and endoderm epithelial cells also provide significant amounts of *IGF-1* and *IGF-2*, while progenitors and immature thyrocytes express *IGF1R* and mature thyrocytes mainly express *IGF2R*. On the other hand, we also observed that fibroblasts and cardiovascular cells express significant amounts of *WNT2*, *WNT5A*, *TGFb1*, and *TGFb2*, whereas thyroid cells express their respective receptors (Extended data Fig. 3c-d). As described previously, in our model, inhibition of TGFβ signaling leads to enhanced thyroid maturation, and this effect may also be related to repression of such signals from mesodermal-like cells.

Promotion of thyroid hormone synthesis

Despite the cell differentiation and follicular organization at day 45, single-cell RNA profiling revealed that a substantial proportion of the thyrocyte population was not fully mature, which may explain the lack of TH detection at this stage. To promote functionality, we kept the thyroid cells in culture for a longer period of time, mimicking the *in vivo* thyroid maturation.

Complete in vitro human thyroid maturation and thyroid hormone synthesis: Human thyroid development begins around day 20 post fertilization, while completed organogenesis and TH

production can be detected at day 70 [32,33]. Based on the time required for thyroid full maturation and TH synthesis *in vivo*, we kept the organoids growth for two additional weeks using the same conditioned medium (Fig. 1a). Immunostaining revealed a large proportion of well-organized follicles expressing NKX2-1, E-CADHERIN (Fig. 2a) and TG which accumulated mainly in the lumen (Fig. 2b). In addition, marked TPO staining was observed in most follicular structures, with accumulation at the apical membrane indicating an enhancement of maturation (Fig. 2c). Finally, prolongation of the differentiation protocol resulted in TH synthesis, as evidenced by the detection of T4 in the lumen of hESC-derived thyroid follicles (Fig. 2d).

Assessment of in vivo functionality of hESC-derived thyroid follicles: To evaluate the *in vivo* functionality of hESC-derived thyroid follicles, the recovery of TH was measured in NOD-SCID mice whose thyroid gland was ablated with radioactive iodine (RAI) following low-iodine diet to enhance thyroidal RAI uptake. Thyroid ablation was confirmed after 4 weeks by SPEC-CT imaging with ^{123}I. Organoids were harvested and filtered at day 45 to remove most isolated cells and transplanted under the kidney capsule of mice with intact and ablated thyroid glands (Fig. 3a). Due to technical problems caused by the radiosensitivity of immunodeficient mice [38,39], 60% of the irradiated animals died during the experimental period. At the end of the experiment, 6 non-transplanted and 4 transplanted mice had survived and could be compared with 6 untreated animals that served as controls.

Histological evaluation of the renal region five weeks after transplantation showed successful implantation of the transplanted organoids in the host niche (Fig. 3b). HE staining showed numerous follicles organized in a manner characteristic of thyroid tissue (Fig. 3b and Extended data Fig. 4a). The presence of blood vessels in close proximity to the thyroid follicles is essential for the TH release and transport to target tissues. Indeed, blood vessels and stromal cells could be observed in the vicinity of the thyroid follicles (Extended data Fig. 4a-b). Immunostaining for the platelet-derived endothelial cell adhesion molecule CD31 revealed a

dense network of small blood vessels surrounding the thyroid follicles, demonstrating the formation of classic angio-follicular units (Extended data Fig. 4b). The absence of staining overlap between CD31 and Human Nuclear Antigen (HNA) provided unequivocal evidence that the vessels originated from host cells (Extended data Fig. 4b). On the other hand, the stromal cells were derived from the grafted cells since they co-expressed HNA and a-SMA (Extended data Fig. 4c). HE staining showed that the derived follicular epithelium included both active follicles, which appeared cuboidal to low columnar, and inactive ones, in which the cells were squamous (Fig. 4d). Further immunohistochemical analysis supported the formation of functional thyroid follicles (NKX2-1+) at the graft site, including cell polarization labeled by E-Cadherin, TG cytosolic expression and deposition in the luminal compartment, and the appearance of TPO in the cytoplasm and mainly at the apical membrane (Fig. 3c). The transplanted tissue had a similar thyroid gene expression signature compared to human thyroid tissue (Extended data Fig. 4e).

SPECT-CT imaging was used to track the human thyroid graft performance, by the ability of NIS-dependent iodide uptake by thyroid tissue [40]. Images were acquired four weeks after transplantation and showed a strong uptake signal in the neck (where the thyroid gland is located) of non-ablated mice. In thyroid gland ablated transplanted mice, ^{123}I uptake was markedly decreased in the neck, but a very strong signal was detectable at the site of transplantation, near the kidney (Fig. 4a). ^{123}I quantification in SPECT images expressed as percent injected dose (% ID [40]) confirmed the uptake capacity of the transplanted tissue, with a % ID slightly lower compared to the thyroid tissue, while very low uptake values were detected in the neck of the hypothyroid non-transplanted mice (1.66 (0.96-2.14); 2.40 (1.72-4.91) and 0.010 (0.0023-0.032) % ID, respectively; $p<0.01$; Fig. 4a-b).

More importantly, transplanted animals presented a marked increase in plasma T4 levels (1.26 (0.86-2.49) μg/dl) compared to barely detectable plasma T4 levels in non-transplanted animals

(0.11 (0.06-0.23) µg/dl), however still lower than controls non-irradiated (3.63 (3.35-3.80) (Fig. 4c). Evidence of functionality of the transplanted tissue is also provided by immunostaining for T4, which shows numerous active follicles with strong T4 signal in the luminal compartment (Fig. 4d). Considering the challenges of inducing thyroid ablation and transplanting human cells in immunodeficient mice, which are highly sensitive to radiations [38,39], here we present a proof of concept trial showing that human functional thyroid tissue generated from pluripotent stem cells can be grafted and keep the functionality *in vivo*, producing THs and increasing T4 levels in hypothyroid animals.

Conclusions and perspectives

The generation of functional human thyroid follicles *in vitro* has proven to be extremely challenging, compared to mouse-derived equivalents. Although the generation of thyrocytes or thyroid follicles from human stem cells has been reported [10–14], the present study is the first to demonstrate hESC-derived thyroid follicles that produce TH *in vitro* and *in vivo* after transplantation into thyroid gland ablated mice. Our model of human thyroid organoids that function upon transplantation provides valuable source of knowledge to improve our understanding of gene expression dynamics and mechanisms involved in thyroid differentiation and maturation. It could be used as a new diagnostic tool to study of the mechanisms leading to congenital hypothyroidism. Moreover, this model, although still in need of improvement, provides a proof of concept that generating autologous human thyroid tissue to maintain TH is within reach.

METHODS SUMMARY

The human NKX2-1$^{WT/GFP}$ ESC line [25] was genetically engineered to integrate the sequences of *NXK2-1* and *PAX8* genes using lentivirus infection produced with the TRE/rtTA_NKX2-1-PAX8 vector (Extended data Fig. 1b). The modified hESC were cultured in embryoid bodies (EBs) using the hanging drop method [20], embedded in growth factor-reduced Matrigel, and cultured in 12-well plates. Subsequent exposure to Activin A (AA), Doxycycline (Dox), cAMP, rhTSH, dexamethasone, and SB431542 was performed as described in Fig. 1a. During *in vitro* differentiation, organoids were subjected to extensive transcriptomic characterization by qRT-PCR, bulk RNAseq, and single-cell RNAseq, while morphological changes were assessed by live imaging and immunofluorescence. NKX2-1^{GFP+} cell population expansion and proliferation were quantitatively measured by flow cytometry. *In vivo* studies were performed using NOD-SCID mice, who's thyroid glands were ablated as previously described [16,41]. For the transplantation studies, cultures were digested with a collagenase/dispase enzyme solution for 45 days and the enriched ESC-derived thyroid follicular population was transplanted under the kidney capsule. SPECT-CT images were acquired 4 weeks after transplantation, while T4 plasma levels and histological analyzes were performed 5 weeks after transplantation.

References

1. Vanderpump, M. P. J. The epidemiology of thyroid disease. *British Medical Bulletin* **99**, 39–51 (2011).
2. Garmendia Madariaga, A., Santos Palacios, S., Guillén-Grima, F. & Galofré, J. C. The Incidence and Prevalence of Thyroid Dysfunction in Europe: A Meta-Analysis. *The Journal of Clinical Endocrinology & Metabolism* **99**, 923–931 (2014).
3. Taylor, P. N. *et al.* Global epidemiology of hyperthyroidism and hypothyroidism. *Nature Reviews Endocrinology* vol. 14 301–316 (2018).

4. Dew, R. *et al.* Clinical, behavioural and pharmacogenomic factors influencing the response to levothyroxine therapy in patients with primary hypothyroidism-protocol for a systematic review. *Systematic reviews* **6**, 60 (2017).

5. Kraut, E. & Farahani, P. A Systematic Review of Clinical Practice Guidelines' Recommendations on Levothyroxine Therapy Alone versus Combination Therapy (LT4 plus LT3) for Hypothyroidism. *Clinical & Investigative Medicine* **38**, (2015).

6. Watt, T. *et al.* The thyroid-related quality of life measure ThyPRO has good responsiveness and ability to detect relevant treatment effects. *Journal of Clinical Endocrinology and Metabolism* **99**, 3708–3717 (2014).

7. Saravanan, P. *et al. Psychological well-being in patients on "adequate" doses of L-thyroxine: results of a large, controlled community-based questionnaire study*. *Clinical Endocrinology* vol. 57 (2002).

8. Clevers, H. Modeling Development and Disease with Organoids. *Cell* vol. 165 1586–1597 (2016).

9. Kim, J., Koo, B. K. & Knoblich, J. A. Human organoids: model systems for human biology and medicine. *Nature Reviews Molecular Cell Biology* vol. 21 571–584 (2020).

10. Kurmann, A. A. *et al.* Regeneration of Thyroid Function by Transplantation of Differentiated Pluripotent Stem Cells. *Cell Stem Cell* **17**, 527–542 (2015).

11. Ma, R., Latif, R. & Davies, T. F. Human embryonic stem cells form functional thyroid follicles. *Thyroid : official journal of the American Thyroid Association* **25**, 455–461 (2015).

12. Ma, R., Morshed, S. A., Latif, R. & Davies, T. F. TAZ Induction Directs Differentiation of Thyroid Follicular Cells from Human Embryonic Stem Cells. *Thyroid : official journal of the American Thyroid Association* **27**, 292–299 (2017).

13. Serra, M. *et al.* Pluripotent stem cell differentiation reveals distinct developmental pathways regulating Lung-Versus Thyroid-Lineage specification. *Development (Cambridge)* **144**, 3879–3893 (2017).

14. Ma, R., Shi, R., Morshed, S. A., Latif, R. & Davies, T. F. Derivation and 97% Purification of Human Thyroid Cells From Dermal Fibroblasts. *Frontiers in endocrinology* **11**, 446 (2020).

15. Ogundipe, V. M. L. *et al.* Generation and Differentiation of Adult Tissue-Derived Human Thyroid Organoids. *Stem Cell Reports* **16**, 913–925 (2021).

16. Antonica, F. *et al.* Generation of functional thyroid from embryonic stem cells. *Nature* **491**, 66–71 (2012).

17. Longmire, T. A. *et al.* Efficient derivation of purified lung and thyroid progenitors from embryonic stem cells. *Cell Stem Cell* **10**, 398–411 (2012).

18. Ma, R., Latif, R. & Davies, T. F. Thyroid follicle formation and thyroglobulin expression in multipotent endodermal stem cells. *Thyroid* **23**, 385–391 (2013).

19. Dame, K. *et al.* Thyroid Progenitors Are Robustly Derived from Embryonic Stem Cells through Transient, Developmental Stage-Specific Overexpression of Nkx2-1. *Stem Cell Reports* **8**, 216–225 (2017).

20. Bondue, A. *et al.* Mesp1 Acts as a Master Regulator of Multipotent Cardiovascular Progenitor Specification. *Cell Stem Cell* **3**, 69–84 (2008).

21. Mazzoni, E. O. *et al.* Synergistic binding of transcription factors to cell-specific enhancers programs motor neuron identity. *Nature neuroscience* **16**, 1219–1227 (2013).

22. Moreau, T. *et al.* Large-scale production of megakaryocytes from human pluripotent stem cells by chemically defined forward programming. *Nature communications* **7**, 11208 (2016).

346 23. Pawlowski, M. *et al.* Inducible and Deterministic Forward Programming of Human
347 Pluripotent Stem Cells into Neurons, Skeletal Myocytes, and Oligodendrocytes. *Stem*
348 *cell reports* **8**, 803–812 (2017).
349 24. de Felice, M. & di Lauro, R. Thyroid development and its disorders: Genetics and
350 molecular mechanisms. *Endocrine Reviews* vol. 25 722–746 (2004).
351 25. Goulburn, A. L. *et al.* A targeted NKX2.1 human embryonic stem cell reporter line
352 enables identification of human basal forebrain derivatives. *Stem Cells* **29**, 462–473
353 (2011).
354 26. Vassart, G. & Dumont, J. E. *The Thyrotropin Receptor and the Regulation of Thyrocyte*
355 *Function and Growth**. vol. 13 (1992).
356 27. Mori, K., Mori, M., Stone, S., Braverman, L. & DeVito, W. Increased expression of
357 tumor necrosis factor-alpha and decreased expression of thyroglobulin and thyroid
358 peroxidase mRNA levels in the thyroids of iodide-treated BB/Wor rats. *European*
359 *Journal of Endocrinology* **139**, (1998).
360 28. Dohán, O. *et al.* The sodium/iodide symporter (NIS): Characterization, regulation, and
361 medical significance. *Endocrine Reviews* vol. 24 48–77 (2003).
362 29. Mincione, G. *et al.* EGF and TGF-β1 effects on thyroid function. *Journal of Thyroid*
363 *Research* vol. 2011 (2011).
364 30. Faria, M. *et al.* TNFα-mediated activation of NF-κB downregulates sodium-iodide
365 symporter expression in thyroid cells. *PloS one* **15**, e0228794–e0228794 (2020).
366 31. Romitti, M. *et al.* Single-Cell Trajectory Inference Guided Enhancement of Thyroid
367 Maturation In Vitro Using TGF-Beta Inhibition. *Frontiers in Endocrinology* **12**, (2021).
368 32. Fernández, L. P., López-Márquez, A. & Santisteban, P. Thyroid transcription factors in
369 development, differentiation and disease. *Nature Reviews Endocrinology* vol. 11 29–42
370 (2015).

371 33. Dom, G. *et al.* Transcriptomic Signature of Human Embryonic Thyroid Reveals
372 Transition From Differentiation to Functional Maturation. *Frontiers in Cell and*
373 *Developmental Biology* **9**, (2021).
374 34. Lazzaro, D., Price, M., de Felice, M. & Lauro, R. di. *The transcription factor TTF-1 is*
375 *expressed at the onset of thyroid and lung morphogenesis and in restricted regions of*
376 *the foetal brain*. *Development* vol. 113 (1991).
377 35. Haerlingen, B. *et al.* Small-Molecule Screening in Zebrafish Embryos Identifies
378 Signaling Pathways Regulating Early Thyroid Development. *Thyroid* **29**, (2019).
379 36. Vandernoot, I. *et al.* Enhanced Canonical Wnt Signaling During Early Zebrafish
380 Development Perturbs the Interaction of Cardiac Mesoderm and Pharyngeal Endoderm
381 and Causes Thyroid Specification Defects. *Thyroid* **31**, (2021).
382 37. Smith, T. J. Insulin-Like Growth Factor Pathway and the Thyroid. *Frontiers in*
383 *endocrinology* **12**, 653627 (2021).
384 38. Fulop, G. M. & Phillips, R. A. The scid mutation in mice causes a general defect in DNA
385 repair. *Nature* **347**, (1990).
386 39. Biedermann, K. A., Sun, J. R., Giaccia, A. J., Tosto, L. M. & Brown, J. M. scid mutation
387 in mice confers hypersensitivity to ionizing radiation and a deficiency in DNA double-
388 strand break repair. *Proceedings of the National Academy of Sciences of the United*
389 *States of America* **88**, 1394–1397 (1991).
390 40. Brandt, M. P. *et al.* Micro-single-photon emission computed tomography image
391 acquisition and quantification of sodium-iodide symporter-mediated radionuclide
392 accumulation in mouse thyroid and salivary glands. *Thyroid* **22**, 617–624 (2012).
393 41. Abel, E. D. *et al.* Divergent roles for thyroid hormone receptor β isoforms in the
394 endocrine axis and auditory system. *Journal of Clinical Investigation* **104**, (1999).
395

Figures

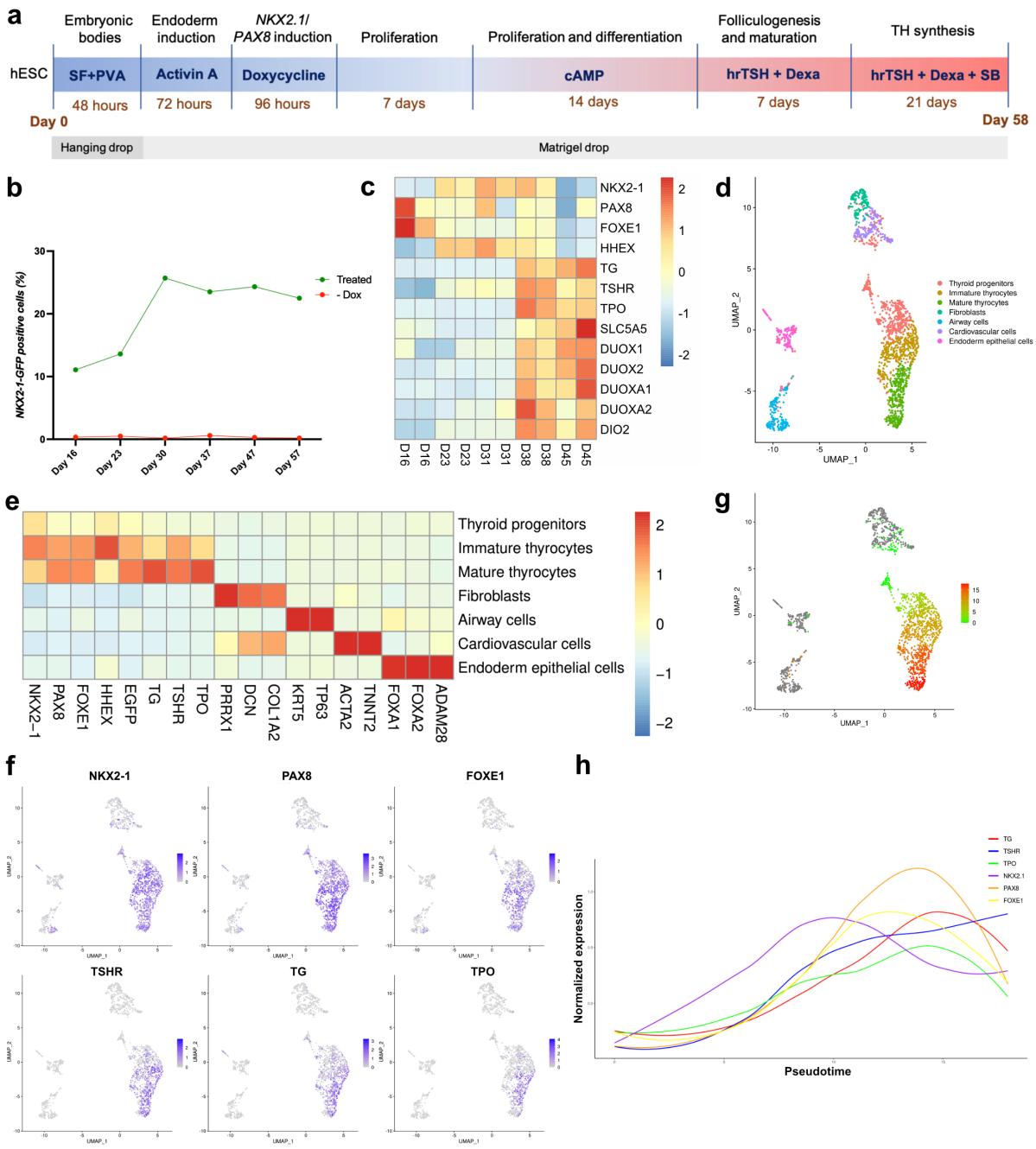


Figure 1. Transient overexpression of *NKX2-1* and *PAX8* promotes differentiation of human ESCs into thyroid follicular cells. (a) Schematic representation of the protocol leading to thyroid follicle differentiation from human ESCs. (b) Quantification by flow cytometry of the proportion of NKX2-1^{GFP+} cells during the differentiation protocol. (c) Heatmap of normalized bulk RNA-Seq expression of thyroid genes in NKX2-1^{GFP+} cells at

different stages of the thyroid differentiation protocol. Rows represent markers and columns represent specific time points. Color values in the heatmap represent mean expression levels. (d) Single cell RNA-Seq unsupervised clustering of *in vitro* derived human thyroid organoid model cells (day 45). Each cluster is represented by a specific color. (e) Heatmap showing normalized expression of selected marker genes with rows representing cell clusters, while columns represent genes. The intensity of the color in each square indicates the mean expression within the cluster. (f) UMAP overlaid with gene expression plots for thyrocyte markers. Color indicates normalized expression. (g) Diffusion analysis of thyrocyte lineage with thyroid progenitor cells as root cells. UMAP overlaid with pseudotime. Color in pseudotime plot indicates order of cell progression. (h) Expression trends of thyroid genes along the pseudotime trajectory.

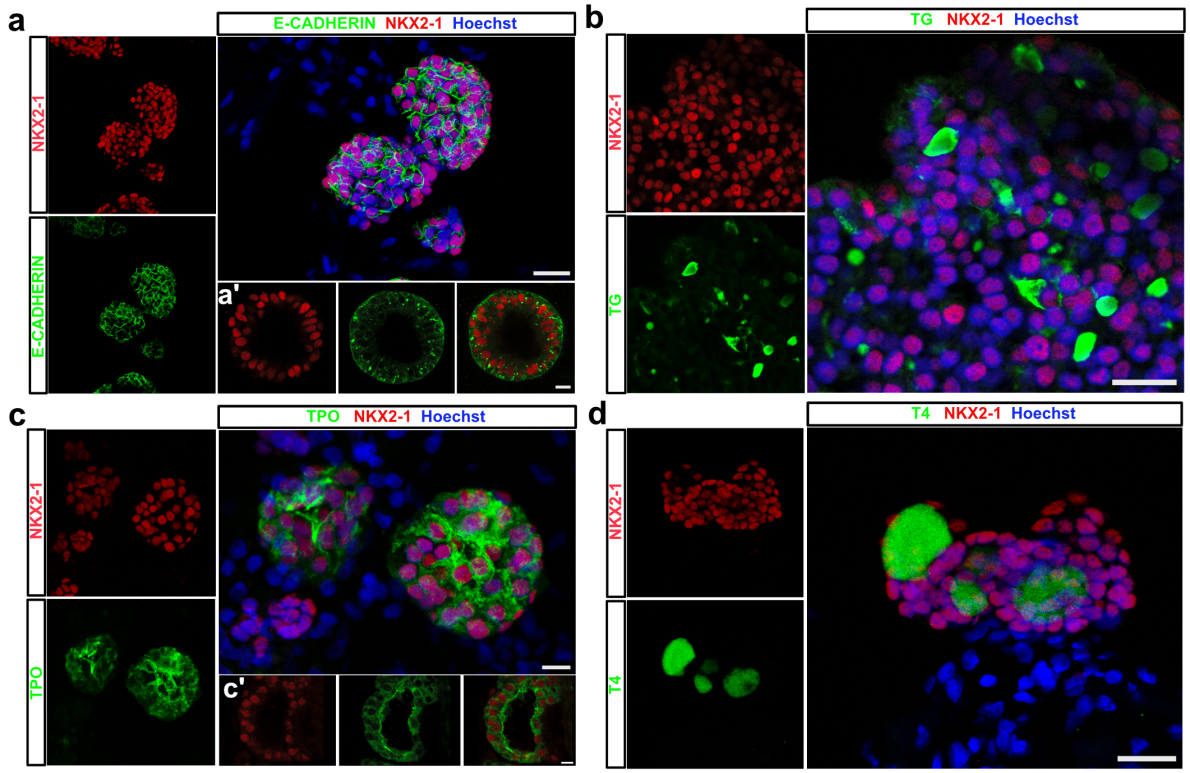


Figure 2. Characterization of human ESC-derived thyroid follicular structures by immunostaining. (a-d) Confocal immunofluorescence images at day 58 of the differentiation protocol. Three-dimensional follicular structures co-expressing NKX2-1 and (a) E-CADHERIN (a'; follicle at high magnification), (b) TG with cytosolic and luminal accumulation, (c) TPO cytoplasmic and apical membrane expression (c'; follicle at high magnification), and (d) T4 storage in the lumenal compartment. Scale bars, 20 µm and 10 µm for high magnification follicles.

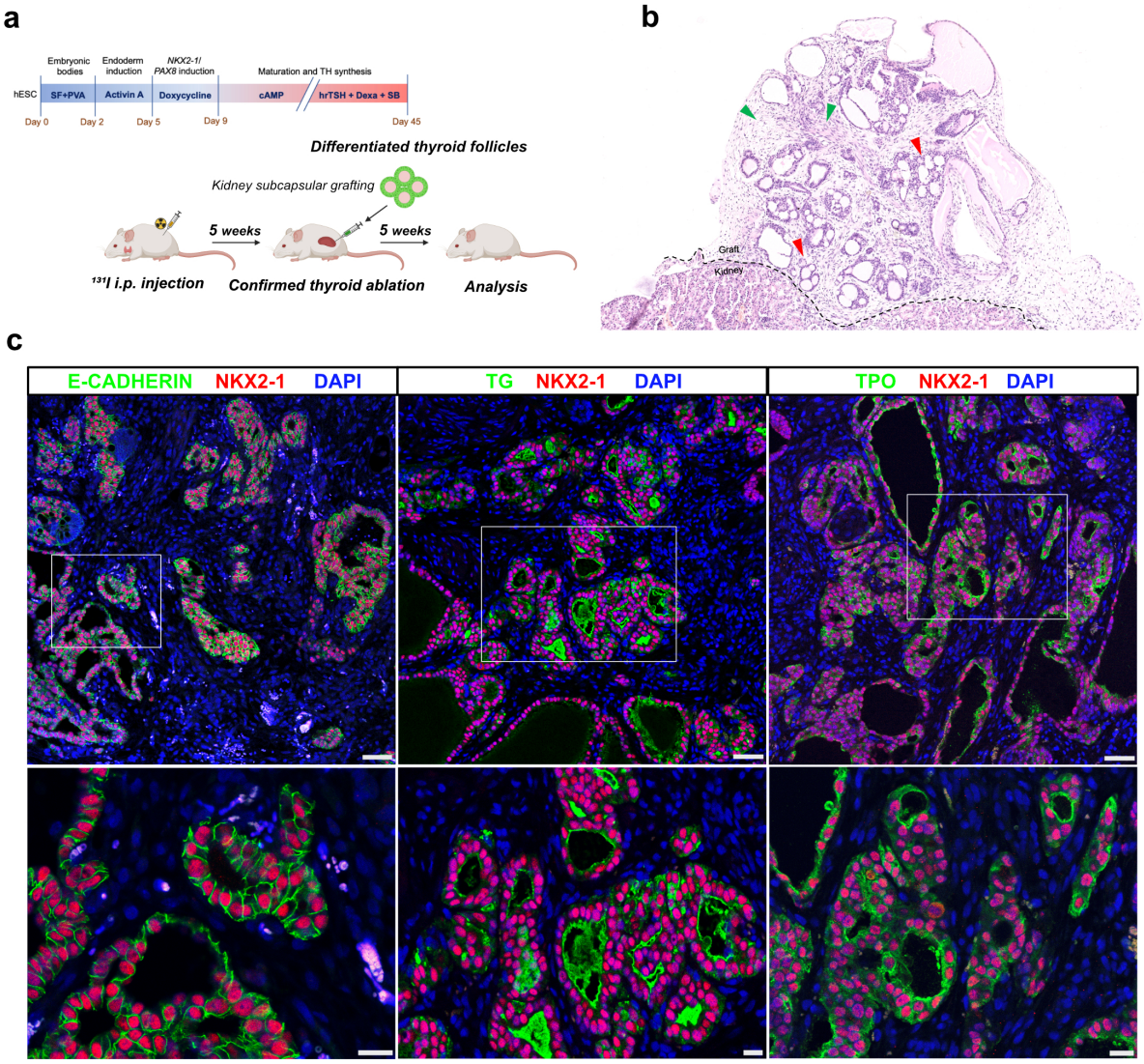


Figure 3. Transplantation of hESC-derived enriched thyroid follicles into NOD-SCID mice. (a) Schematic representation of the hESC-derived thyroid follicles transplantation \under the kidney capsule protocol in NOD-SCID untreated mice or previously thyroid RAI ablated by intraperitoneal ^{131}I injection. (b-c) Histological analysis of the grafted sections 5 weeks after transplantation. (b) Hematoxylin and eosin-stained sections of the transplanted organoids show the localization of the generated human thyroid follicles in the cortical region of the host kidney. Red arrows show the organization of the monolayer epithelium of the transplanted tissue surrounded by stromal cells (green arrows). (c) Confocal images show co-expression of NKX2-1 and E-CADHERIN in the monolayered epithelially organized follicular structures.

437 The grafted tissue shows that TG is principally accumulated in the luminal compartment,
438 whereas TPO is strongly expressed in the apical membrane. Scale bars, 50μm (upper images)
439 and 20μm (zoomed lower images).
440

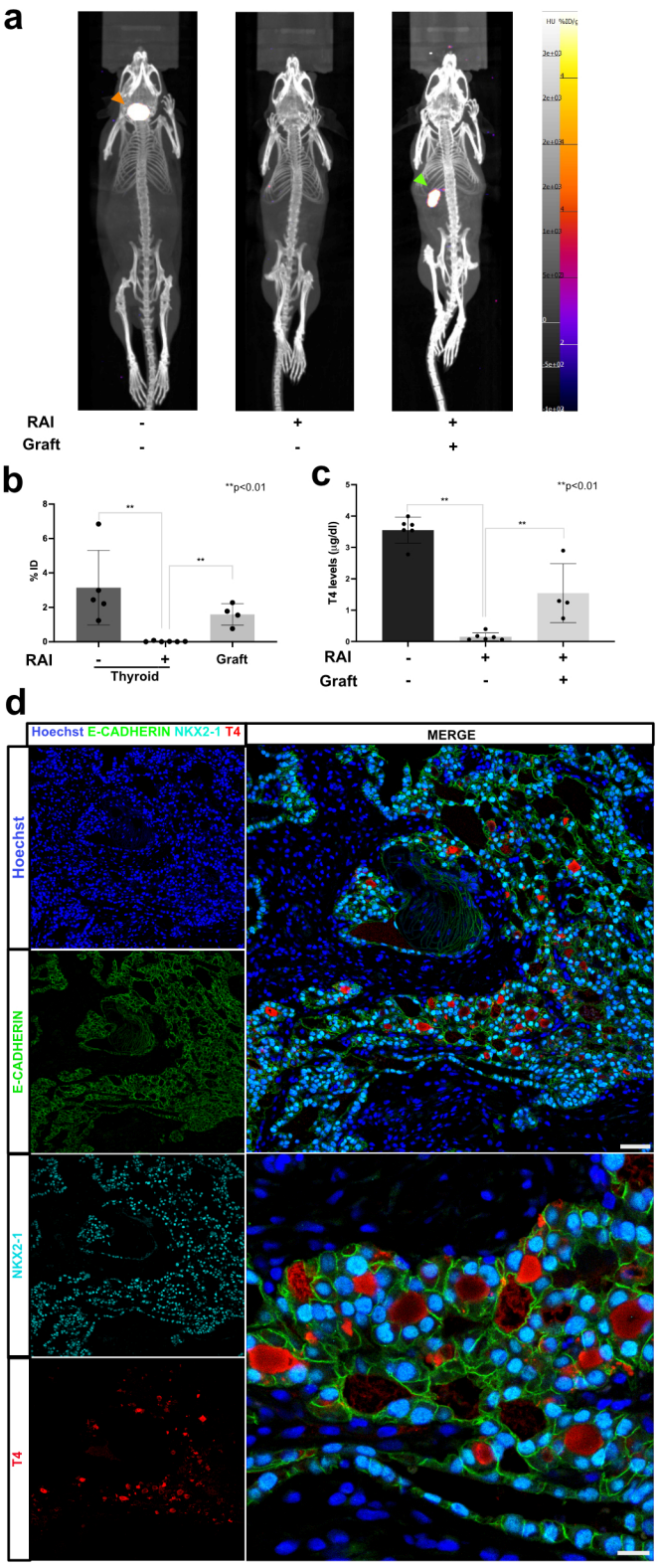


Figure 4. *In vivo* functionality of transplanted human ESC-derived thyroid follicles. (a) Maximum intensity projections generated from SPEC/CT images of non-irradiated and non-transplanted (left), RAI-ablated and non-transplanted (middle), and RAI-ablated and

transplanted (right) mice. Images were obtained four weeks after organoids transplantation. The ^{123}I uptake in the mouse thyroid tissue is shown by the orange arrow, while the signal from the human thyroid tissue (graft) is highlighted by the green arrow. The color scales are chosen to represent the radioactivity uptake in PET images expressed as standardized uptake values (SUV) (0 to 8, from light yellow to dark blue). (b) Quantification of ^{123}I uptake in SPECT images expressed as percentage of injected dose (% ID) in the intact (non-irradiated) (2.44 (1.72-4.91) % ID; n=5) or RAI-ablated thyroid region (0.01 (0.002-0.03) % ID; n=6), and grafted tissue (1.66 (0.96-2.14) % ID; n=4). (c) Comparison of plasma T4 levels among controls (3.63 (3.35-3.80) µg/dl; n=6), irradiated/non-transplanted (0.11 (0.06-0.23) µg/dl; n=6) and irradiated/transplanted mice (1.26 (0.86-2.49) µg/dl; n=4). (d) NKX2-1, E-CADHERIN and T4 immunostaining demonstrate the presence of hESC-derived follicles in the transplanted area with specific accumulation of T4 within the lumen of several structures. Mann-Whitney test was used for statistical analysis. **p<0.01.

Extended data

METHODS

Generation of tetracycline-induced hESC line: The human embryonic stem cell line HES3 used in this study was genetically modified at the NKX2-1 locus to allow insertion of sequences encoding green fluorescent protein (GFP), resulting in the NKX2-1$^{wt/GFP}$ hESC line as previously described [25] (Extended data Fig. 1a). To generate an inducible NKX2-1-PAX8 hESC line, we cloned the coding sequences of the *NKX2-1* and *PAX8* genes, separated by a IRES sequence, into the pInducer20 lentiviral vector (a gift from Stephen Elledge; Addgene plasmid # 44012; http://n2t.net/addgene:44012; RRID: Addgene_44012), which contains the sequences for the TRE/rtTA-inducible system (Extended data Fig. 1b). Lentiviral supernatants were generated by transient transfection of HEK293 cells according to Lipofectamine ™ 2000 (Invitrogen) transfection protocols and harvested 48 h after transfection. To promote integration of sequences into the genome of the NKX2-1$^{wt/GFP}$ HES3 line, hESCs were plated at high density (1:3) in a Matrigel-coated 6-well culture dish and infected with 50 ml of lentivirus supernatant and 6 µg/ml polybrene for 18-20 hours in mTeSR medium (Stem Cell). Positive clones were selected with 300 µg/ml neomycin (Invitrogen). Clones were treated with 1 mg/ml doxycycline (Sigma) for 48 h and screened by immunostaining against NKX2-1 and PAX8 to verify transgene expression. Selected clones were tested for genomic integrity using G-banding technique according to the protocol described previously [42]. Pluripotency was assessed by testing the ability of the clones to differentiate into cells from the three germ layers. Cells were cultured in basal differentiation medium (Extended data Table 1) for 21 days and the formation of endoderm, mesoderm and ectoderm cells was assessed by immunofluorescence staining against AFP, α-SMA and β-III tubulin, respectively. The hESC-

NKX2-1-PAX8 line was registered and approved by the European Human Pluripotent Stem Cell Registry (hPSCreg) as ESIBIe003-A-6.

hESC culture and differentiation: Modified hESCs were cultured and propagated on Matrigel-coated 6-well culture dishes in Stem Flex medium (Thermo Scientific, A3349401) supplemented with 100 U/ml Penicillin-Streptomycin (Gibco). For the generation of embryoid bodies (EBs), highly confluent hESCs were detached with 0.5 mM EDTA solution and diluted with 100,000 cells/ml in Stem Flex medium supplemented with 4 mg/ml polyvinyl alcohol (PVA; Sigma) and EBs formation was induced as previously described [16,20]. Briefly, hESCs (2,000 cells per droplet) were cultured in hanging drops for two days, then EBs were collected and embedded in growth factor-reduced Matrigel (BD Biosciences); 50 µl Matrigel drops (containing approximately 20 embryoid bodies per drop) were replated onto 12-well dishes. Embryoid bodies were differentiated and cultured in differentiation medium containing DMEM/F12+Glutamax (Gibco) with 20% FBS (Gibco), 0.1 mM non-essential amino acids (Gibco), 1 mM sodium pyruvate (Gibco), 0.1 mM 2-mercaptoethanol (Sigma), 100 U/ml Penicillin-Streptomycin (Gibco), and 50 µg/ml L-ascorbic acid (Sigma). Cells were supplemented with 50 ng/ml Activin A (Cell GS) for three days to induce foregut endoderm. Expression of *NKX2-1* and *PAX8* was induced by incubation with 1 mg/ml doxycycline (Dox; Sigma) for four days. Cells were then cultured in basal differentiation medium for one week to allow expansion of thyroid progenitors, while differentiation and maturation were induced by treatment with 300 µM 8-br-cAMP (Biolog Inc.), 1 mU/ml rhTSH (Genzyme), 50 nM dexamethasone (Dexa; Sigma) and 10 µM SB431542 (Peprotech) where indicated (Figure 1a). Culture medium was changed every 48 hours.

519 **NKX2-1^{GFP+} population assessment – Flow cytometry:** hESCs under the thyroid
520 differentiation protocol were collected each week, from day 16 to day 45, and prepared for
521 flow cytometry immunostaining as follows: Matrigel drops (at least 4 samples per time point)
522 were first digested with HBSS solution containing 10 U/ml dispase II (Roche) and 125 U/ml
523 collagenase type IV (Gibco, Thermo Fisher) for 30-60 min at 37°C; then a single cell
524 suspension was obtained by dissociation with TripLE Express (Thermo Fisher) for 10-15 min
525 incubation at 37°C, the enzymes were inactivated by addition of differentiation medium. After
526 centrifugation, samples were rinsed with PBS and fixed in 1.6% PFA solution in PBS for 15
527 min at RT, followed by cell permeabilization with 0.1% Triton solution in PBS for 15 min at
528 4°C under agitation. After centrifugation, 4% horse serum and 0.5% Tween 20 PBS blocking
529 solution was added for 10 min (4°C with shaking). The primary anti-rabbit KI67 antibody
530 (1:100) was diluted in the blocking solution and samples were incubated for 30 min (4°C with
531 shaking). Cells were then rinsed three times with wash solution (0.5% BSA and 0.5% Tween
532 in PBS) and then incubated with Cy5-conjugated anti-rabbit antibody (1:300) diluted in
533 blocking solution for 30 min (4°C with shaking). NKX2-1^{GFP+} and K67 expression data were
534 obtained and processed using an LSR-Fortessa X-20 flow cytometer and FACSDiva software
535 (BD Biosciences). Unstained cells and isotype controls were included in all experiments. In
536 addition, the percentage of GFP+ cells was used to estimate the thyroid generation efficiency
537 of our protocol.
538
539 **RNA extraction and quantitative real-time PCR:** For total RNA extraction, human
540 organoids (at different time points), *in vivo* samples, and human thyroid tissue (histologicaly
541 normal thyroid tissue was obtained from a patient undergoing thyroidectomy; Hopital Erasme-
542 ULB Ethics Committee approval; P2016/260), was lysed using RLT lysis buffer supplemented
543 with 1% 2-mercaptoethanol (Sigma), and RNA isolation was performed using the RNeasy

544 micro kit (Qiagen) according to the manufacturer's instructions. For reverse transcription, the
545 Superscript II kit (Invitrogen) was used, and qPCR was performed in triplicates using Takyon
546 (Eurogentec) and CFX Connect Real-Time System (Biorad). Results are presented as
547 linearized values normalized to housekeeping gene, GAPDH (human) or β2-microglobulin
548 (mouse) and the indicated reference value (2-ΔΔCt). Gene expression profile was obtained
549 from at least three independent experiments. Primer sequences are shown in Table 3.
550
551 **RNA-seq and analysis of bulk samples:** Bulk RNA-seq was performed in hESC-
552 differentiated cells every week from day 16 to day 45 of our differentiation protocol (Figure
553 1a). The NKX2-1^{GFP+} cell population was obtained by FACS sorting (FACS Aria; BD
554 Bioscience) after sample preparation was performed as previously described (section "NKX2-
555 1^{GFP+} population expansion assessment - Flow Cytometry"). In brief, 10,000 NKX2-1^{GFP+} cells
556 were directly sorted into 700 µl of Qiazol lysis reagent (Qiagen) and RNA isolation was
557 performed using the miRNeasy micro kit (Qiagen) according to the manufacturer's instructions.
558 RNA concentration and quality were evaluated using Bioanalyser 2100 (Agilent) and RNA
559 6000 Nano Kit (Agilent). RNA integrity was preserved, and no genomic DNA contamination
560 was detected. Ovarion Solo RNA-seq Systems (NuGen) was used as indicated by the
561 manufacturer, resulting in high-quality indexed cDNA libraries quantified with the Quant-iT
562 PicoGreen kit (Life Sciences) and Infinite F200 Pro plate reader (Tecan); DNA fragment size
563 distribution was examined with the 2100 Bioanalyzer (Agilent) using the DNA 1000 kit
564 (Agilent). Multiplexed libraries (10ρM) were loaded onto flow cells and sequenced on the
565 HiSeq 1500 system (Illumina) in high-output mode using the HiSeq Cluster Kit v4 (Illumina).
566 Approximately 10 million paired-end reads were obtained per sample. After removal of low-
567 quality bases and Illumina adapter sequences using Trimmomatic software [43], sequence reads
568 were aligned against the human reference genome (Hg19) using HiSat2 software [44]. Raw reads

569 were determined with HTSeq software [45] using the Ensembl genome annotation GRCh38.p13.
570 Normalization and differential expression analyzes were performed with two biological
571 replicates per sample using the website iDEP version 0.93 [46]. Genes for which expression
572 values were lower than 5 were filtered out. The fold changes of mean gene expression for the
573 duplicates were used to calculate the level of differential gene expression.
574
575 **Single cell RNAseq characterization of thyroid organoids:** Cells originating from human
576 thyroid differentiation protocol, at day 45, were isolated for scRNAseq profiling, following the
577 procedures previously described [31]. Single cell suspension preparation and FACS cell sorting
578 were performed as previously mentioned ("Cell proliferation assessment – Flow cytometry"
579 and RNA-seq and analysis of bulk samples sections). Different proportions of viable NKX2-
580 1/GFP+ (60%) and NKX2-1/GFP- (40%) cells were sorted to guarantee representation of the
581 distinct cell types present in the organoid culture. Sorted cells were collected in PBS at a density
582 of 800cells/ul and diluted accordingly to kit's instruction (10x Genomics Chromium Single
583 Cell 3' v3). Around 6,000 cells were loaded onto a channel of the Chromium Single Cell 3′
584 microfluidic chip and barcoded with a 10X Chromium controller followed by RNA reverse
585 transcription and amplification according to manufacturer's recommendations (10X
586 Genomics). Library preparation was performed based on 10x Genomics guidelines. Libraries
587 were sequenced using Illumina NovaSeq 6000 system.
588
589 **Single cell RNAseq data analysis:** Raw sequencing data was aligned, annotated,
590 demultiplexed and filtered using Cell Ranger Software (v.6.0.1) with a custom-built reference.
591 The custom-built reference was based on the human reference genome GRCh38 and gene
592 annotation Ensembl 98 in which the EGFP sequence was included. The new reference was
593 generated using the cellranger mkref function from the Cell Ranger Software. Analyses were

done using R 4.1.0 and Seurat version 4.0.3 [47]. Briefly, raw counts from Cell Ranger were loaded and the "background soup" was removed using SoupX [48]. The background soup refers to ambient RNA molecules contaminating cell-containing droplets, a common problem in droplet-based single cell RNA-sequencing technologies. Decontaminated UMIs were then filtered to discard any doublet (droplet containing two cells instead of 1) using DoubletFinder [49]. Finally, cells containing less than 200 unique genes or more than 26% of UMI counts related to mitochondrial genes were discarded. The 26% threshold was selected to discard dying cells while retaining as much barcodes as possible. The resulting library was scaled and normalized using the SCTransform function from Seurat. Cell cycle effects and mitochondrial content were used as variables to regress out with SCTransform. Principal component analysis (PCA) was computed using the 3000 first variable features, and the top 30 principal components were used for SNN graph construction, clustering (resolution 1) and UMAP embedding using Seurat's functions and recommended methods. Cluster annotation was based on marker genes obtained using Seurat's FindAllMarkers function and literature survey. Pseudotime analysis in thyroid populations was performed using Monocle3 [50] with default parameters and with data imported from the Seurat object, selecting thyroid progenitors as root cells. Pseudotime-related plots were generated using the FeaturePlot function from Seurat and the geom_smooth function from ggplot2. Receptor-ligand interaction analysis was done with CellPhoneDB, which consists in a public repository of ligands, receptors and their interactions enabling a comprehensive and systematic analysis of cell–cell communication [51]. CellphoneDB was run using the statistical method with default parameters. A manually selected list of biologically relevant ligand-receptor pairs displaying statistically significant interaction was used to create the dot plot showing the interactions of thyroid populations with other cell populations.

Follicles enrichment for *in vivo* transplantation: Thyroid organoids at day 45 of differentiation were washed twice with Hanks's balanced salt solution (HBSS, containing calcium and magnesium; Gibco), then 1 ml of a digestion medium containing 10 U ml dispase II (Roche) and 125 U ml of collagenase type IV (Sigma) diluted in HBSS was added to each well. The organoids were carefully removed using a 5 ml pipette and transferred to a sterile Erlenmeyer and incubated at 37 °C in a water bath with shaking for 45 - 60 min. The release of thyroid follicles was tracked by microscopy (bright field and GFP). When isolated structures were detected, enzymes were inactivated by addition of 10% FBS followed by centrifugation at 500 g for 3 min. Cells were rinsed twice with HBSS and the follicles population was enriched using 30 µm (single cell removal) and 100 µm (follicles enrichment; 30-100 µm size) reverse strainer (Pluriselect). Finally, the 3D-structures were counted and approximately 10,000 structures were resuspended in 65 µl of differentiation medium for *in vivo* transplantation.

RAI-induced hypothyroidism mouse generation, transplantation of hESC-derived thyroid follicles and SPECT-CT imaging: All animal experiments were performed in accordance with local Animal Ethics (Ethical Project CMMI-2020-01). A cohort of 20 five-week-old female non-obese and non-diabetic mice with severe combined immunodeficiency (NOD -SCID) (Charles River Laboratories, France) was placed on an iodine-deficient diet for one week after arrival. In addition, six NOD -SCID mice, not submitted to any treatment were included in the study as external controls. One week after starting the diet (first week), 14 of the 20 mice were injected intraperitoneally with approximately 5.75 MBq (90µL supplemented with 10 µL NaCl 0.9% solution (MiniPlasco, BBraun) Iodide ^{131}I-Injection-IBS.2P (GE Healthcare Belux, Belgium). To confirm the destruction of functional thyroid tissue by ^{131}I injection, SPECT-CT images of Sodium Iodide ^{123}I uptake were obtained on a nanoSPECTPlus (for the SPECT) and a nanoScanPETCT (for the CT) (Mediso, Hungary) equipped with a

643 Minerve rat cell implemented with a mouse insert. In the fourth week, the 20 mice were injected
644 intravenously with 8.75-9.33 MBq ^{123}I 24 hours before imaging. SPECT/CT imaging was
645 performed on two mice in parallel under isoflurane anesthesia (1.8% isoflurane, 2.0 l/min O2)
646 with the following parameters: collimator aperture APT105, 'fast' helicoidal acquisition mode
647 with a duration of 50 s/projection to acquire 1000 counts per projection, scan range of 105 mm,
648 reconstruction in standard mode, i.e. 35% smoothing, 3 iterations and 3 subsets to obtain a
649 voxel size of 750 µm^3. CT was performed with the following parameters: 480 projections,
650 minimum zoom, binning 1:4, 50 kV, 300 ms/proj, scan range of 115 mm. Acquisition data
651 were reconstructed with a Feldkamp-based algorithm generated to obtain a cubic voxel of
652 250 µm^3, using a cosine filter with a cut-off of 100%. Then, one week later (week five) 6
653 irradiated mice were transplanted with thyroid organoids. First, control and thyroid gland
654 ablated mice were treated with 0.01 mg/ml - 50 µl Temgesic (Schering Plow), anesthetized
655 under isoflurane anesthesia, and the eyes/cornea were protected with Vidisic gel (Bausch &
656 Lomb Inc.). Mice were injected with 8 µl of follicle-enriched suspension thyroid organoids
657 (described in "Enrichment of follicles for *in vivo* transplantation") into the unilateral kidney
658 under the capsule using a 30G needle syringe (Hamilton Bonaduz AG) (the kidney was exposed
659 through skin/muscle/peritoneum incision via a dorsolateral approach). The entire cohort of
660 mice was imaged 4 weeks after transplantation (week 9) as described above to assess the iodine
661 uptake capacity of the transplanted tissue. Due to the radiosensitivity of immunodeficient mice
662 [38,39], 30% of the irradiated animals died during the experimental period. At the end of the
663 experiment (week ten), 6 non-transplanted and 4 transplanted mice had survived and could be
664 analyzed. Mice were finally sacrificed, blood collection was performed for the T4 assay, while
665 the kidney and transplanted tissues were harvested for transcriptomic and histological analyzes.
666 Qualitative and quantitative analysis of the images was performed using VivoQuant v3.5
667 software (InVicro, USA). Radioiodine uptake in thyroid tissue and/or graft was evaluated

668 according to the design of volumes of interest (VOI) based on the corresponding radioactive
669 signal. The % injected dose (% ID) was calculated as previously described by Brandt, et al,
670 2012 [40] and results were expressed as % ID/organ [40].
671
672 **Plasma T4 measurement:** Total T4 levels were measured by Mouse/Rat T4 Total ELISA kit
673 (T4044T-100 Calbiotech) according to the manufacturer's instructions.
674
675 **Immunofluorescence staining:** For immunofluorescence staining, cells cultured in monolayer
676 or MTG -drop were fixed in 4% paraformaldehyde (PFA; Sigma) for 2 h at RT, washed three
677 times in PBS, and blocked in 3% bovine serum albumin (BSA; Sigma), 5% horse serum
678 (Invitrogen), and 0.3% Triton X-100 (Sigma) PBS solution for 30 min at room temperature.
679 Primary and secondary antibodies were diluted in a PBS solution of 3% BSA, 1% horse serum,
680 and 0.1% Triton X-100. Primary antibodies were incubated overnight at 4°C, then washed three
681 times and incubated with secondary antibodies for 2 h at room temperature. The nuclei were
682 stained with Hoechst 33342 (Invitrogen). The slides were mounted with Glycergel (Dako). For
683 paraffin embedding, *in vitro* organoids and grafted samples were fixed overnight at 4°C in 4%
684 PFA and kept in 70% ethanol at 4°C for at least 24 hours at 4°C before embedding. Samples
685 were then embedded in paraffin, sectioned (5 µm), mounted on glass slides, deparaffinized,
686 and rehydrated. For histological analysis, sections were stained with hematoxylin and eosin
687 (H&E) according to a routine protocol. For immunostaining, antigen retrieval was performed
688 by incubating the sections for 10 min in the microwave (850 W) in Sodium Citrate Buffer (10
689 mM Sodium Citrate, 0.05% Tween 20, pH 6.0). After cooling, the sections were rinsed with
690 PBS and then blocked with 1% BSA and 10% horse serum PBS solution for 1 h at RT. Primary
691 antibodies were diluted in the blocking solution and incubated overnight at 4°C. The sections
692 were rinsed three times in PBS and incubated with Hoechst 33342 (Invitrogen) and secondary

antibodies diluted in blocking solution for 1 h at room temperature. Slides were mounted with Glycergel (Dako). Information on antibodies and sources are listed in Extended Data Table 2.

Imaging: Fluorescence imaging was performed on a Zeiss LSM510 META confocal microscope, a Zeiss Axio Observer Z1 microscope with AxioCamMR3 camera, and a Leica DMI6000 with DFC365FX camera. Hematoxylin and eosin whole slide images were acquired using a NanoZoomer- SQ digital slide scanner C13140-01 (Hamamatsu) and images were generated using NDP.view 2 software (Hamamatsu).

Statistical analysis: Statistical significance between two groups was tested using the unpaired t test or the nonparametric Mann-Whitney U test, while comparison between multiple groups was performed using one-way ANOVA or Kruskal-Wallis tests. Data are presented as mean ± SD or median (IQR). Differences were considered significant at $p<0.05$. GraphPad Prism version 9 was used for most analyses (GraphPad Software). Data presented are from at least three independent experiments.

Data availability

Bulk RNA-seq and Single-cell RNA-seq data have been deposited in the NCBI Gene Expression Omnibus under accession number GSE181452 and GSE181256, respectively. Source data are provided with this paper.

Code availability

Custom computer script used to generate scRNAseq data are available upon request.

Methods references

42. Campos, P. B., Sartore, R. C., Abdalla, S. N. & Rehen, S. K. Chromosomal spread preparation of human embryonic stem cells for karyotyping. *Journal of Visualized Experiments* (2009) doi:10.3791/1512.

43. Bolger, A. M., Lohse, M. & Usadel, B. Trimmomatic: a flexible trimmer for Illumina sequence data. *Bioinformatics* **30**, (2014).

44. Kim, D., Langmead, B. & Salzberg, S. L. HISAT: a fast spliced aligner with low memory requirements. *Nature Methods* **12**, (2015).

45. Anders, S., Pyl, P. T. & Huber, W. HTSeq--a Python framework to work with high-throughput sequencing data. *Bioinformatics* **31**, (2015).

46. Ge, S. X., Son, E. W. & Yao, R. iDEP: an integrated web application for differential expression and pathway analysis of RNA-Seq data. *BMC Bioinformatics* **19**, (2018).

47. Hao, Y. *et al.* Integrated analysis of multimodal single-cell data. *Cell* **184**, 3573-3587.e29 (2021).

48. Young, M. D. & Behjati, S. SoupX removes ambient RNA contamination from droplet-based single-cell RNA sequencing data. *GigaScience* **9**, (2020).

49. McGinnis, C. S., Murrow, L. M. & Gartner, Z. J. DoubletFinder: Doublet Detection in Single-Cell RNA Sequencing Data Using Artificial Nearest Neighbors. *Cell Systems* **8**, (2019).

50. Cao, J. *et al.* The single-cell transcriptional landscape of mammalian organogenesis. *Nature* **566**, 496–502 (2019).

51. Efremova, M., Vento-Tormo, M., Teichmann, S. A. & Vento-Tormo, R. CellPhoneDB: inferring cell–cell communication from combined expression of multi-subunit ligand–receptor complexes. *Nature Protocols* **15**, (2020).

743 **Acknowledgements**

744 We acknowledge the ULB flow cytometry platform (Christine Dubois), the ULB genomic core
745 facility (F. Libert and A. Lefort), LiMIF platform for confocal microscopy (J.-M.
746 Vanderwinden), Coraline De Maeseneire, Nicolas Passon and Christophe Van Heymbeek
747 (CMMI) for their contribution for the *in vivo* studies. We also acknowledge Professor Andrew
748 G Elefanty for kindly providing human ESC cell line (HES3-NKX2-1$^{WT/GFP}$). Schematic
749 grafting diagram was created with BioRender.com.

750

751 **Author Contributions**

752 M.R. and S.C. developed the project, designed the experiments and analyzed the data. D.F.K
753 generated and selected the hESC-NKX2-1/Pax8 line. M.R., B.F.F and O.M. performed most
754 of the *in vitro* experiments and protocol set up. L.C. performed cell culture, maintenance and
755 karyotype analysis. S.C., M.R and G.D. executed *in vivo* studies. G.D., G.V.S. and S.G.
756 acquired SPECT-CT images and run the % ID analysis. M.R., B.F.F., H.L. analyzed RNA
757 expression and performed IF. P.G. obtained confocal images. M.R. and H.L. performed bulk
758 RNA-Sequencing and analyzed the results. M.R., S.P.S. and B.F.F performed the single-cell
759 RNA-Sequencing. A.T., V.D., B.F.F. S.P.S., S.E.E. and H.L. performed the bioinformatics
760 analysis. S.C. and M.R. wrote the first draft and S.P.S. and S.R. edited the manuscript. S.C.
761 and S.R. acquired funding for the project. All authors contributed to the article and approved
762 the submitted version.

763

764 **Competing interests:** The authors declare no competing interests.

765

766

767

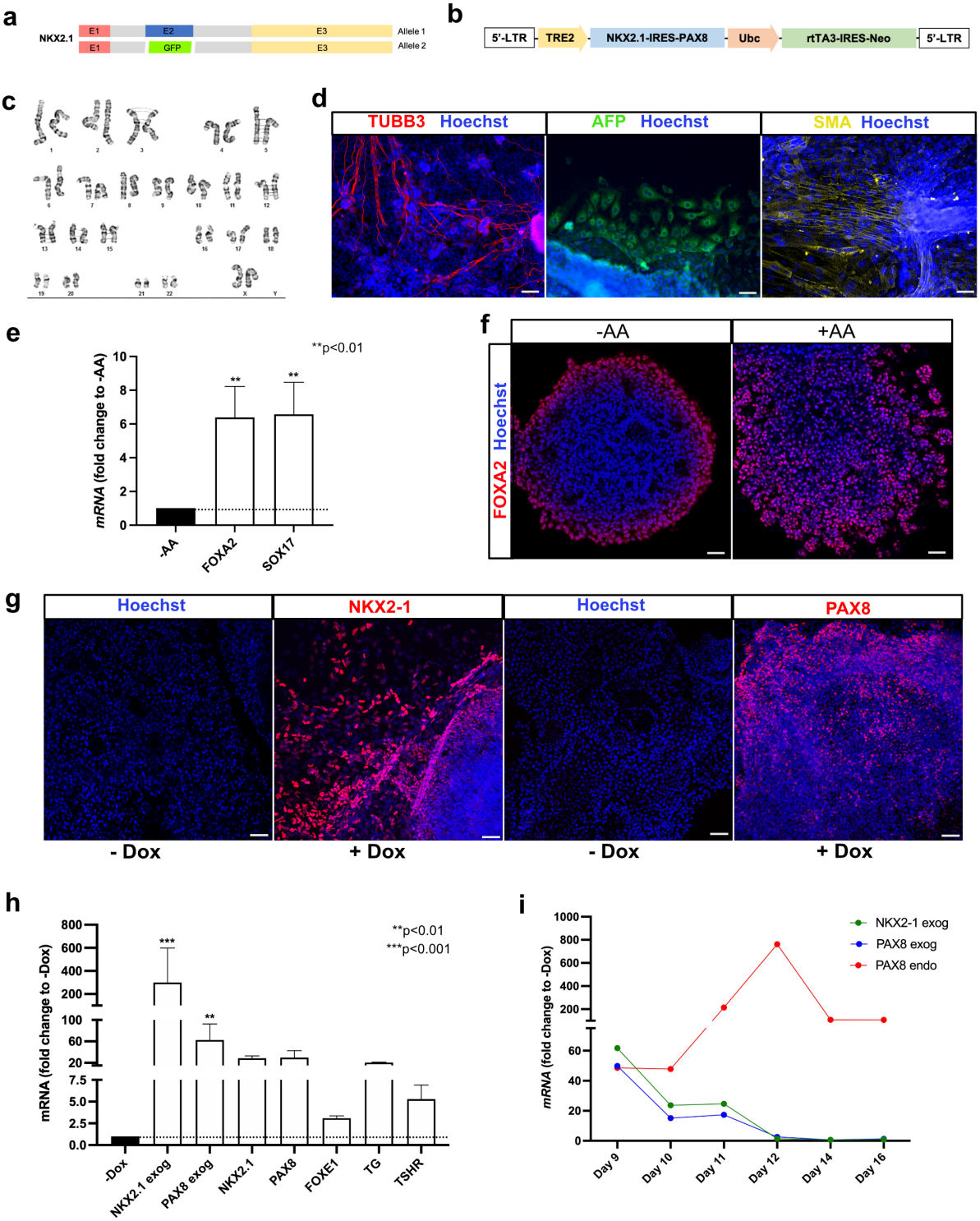
Funding

This work was supported by grants from the Belgian National Fund for Scientific Research (FNRS) (PDR T.0140.14; PDR T.0230.18), the Fonds d'Encouragement à la Recherche de l'Université Libre de Bruxelles (FER-ULB) and it has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 825745. M.R. was supported in part by the Brazilian National Council for Scientific and Technological Development (CNPq; Brazil). Work by S.P.S. was supported by MISU funding from the FNRS (34772792 – SCHISM). The Center for Microscopy and Molecular Imaging (CMMI) is supported by the European Regional Development Fund (ERDF), the Walloon Region, the Fondation ULB, the Fonds Erasme and "Association Vinçotte Nuclear" (AVN). G.D. is supported by European Regional Development Fund (ERDF) and the Walloon Region. M.R was supported by FNRS (Chargé de Recherche) and grant agreement No.825745. B.F.F. and S.R. were supported in part by grant DK15070 from The National Institutes of Health (USA). S.C is Research Director at FNRS.

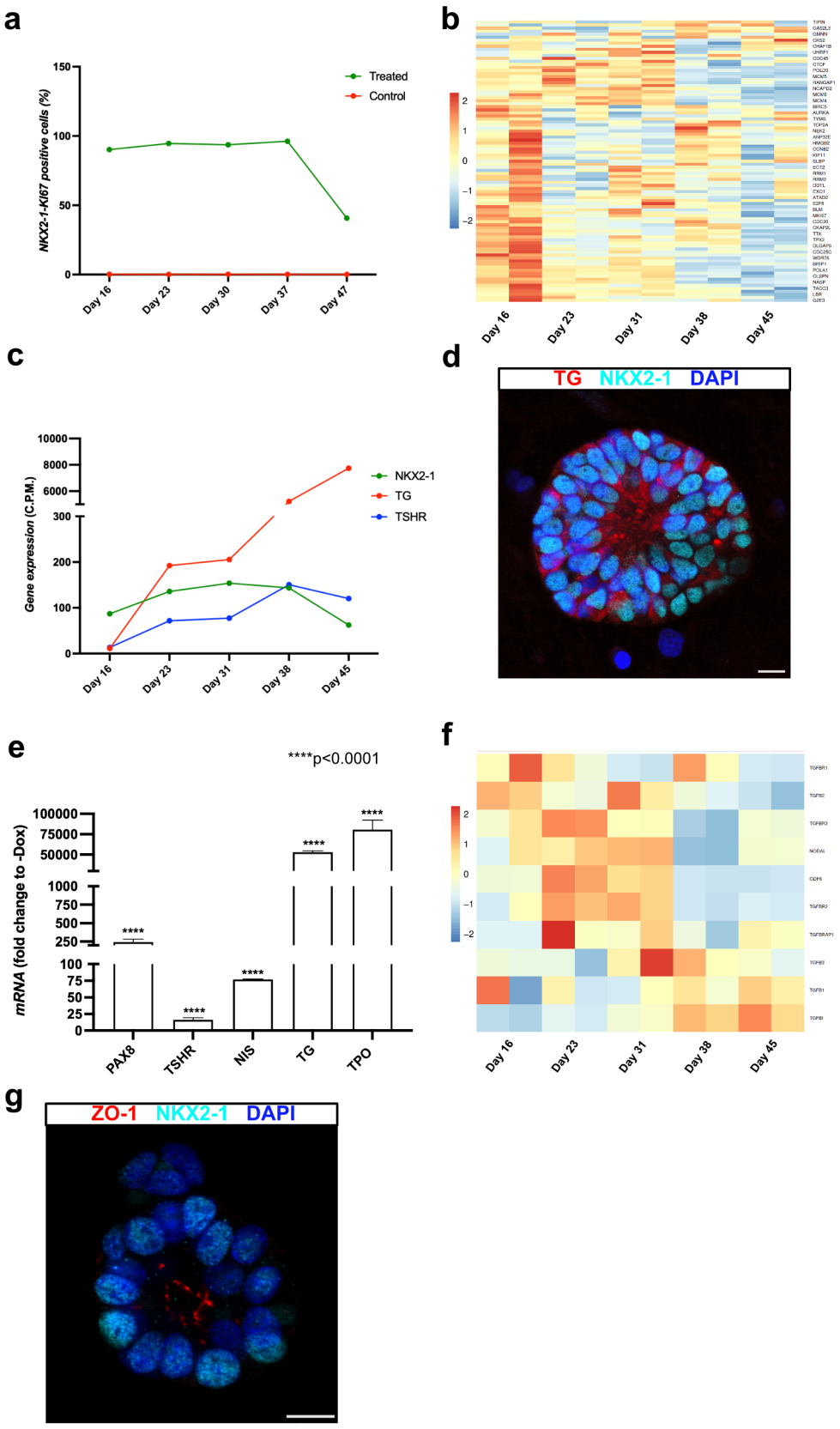
Supplementary Information is available for this paper. Correspondence and requests for materials should be addressed to Sabine Costagliola: sabine.costagliola@ulb.be.

Extended Data

Figures

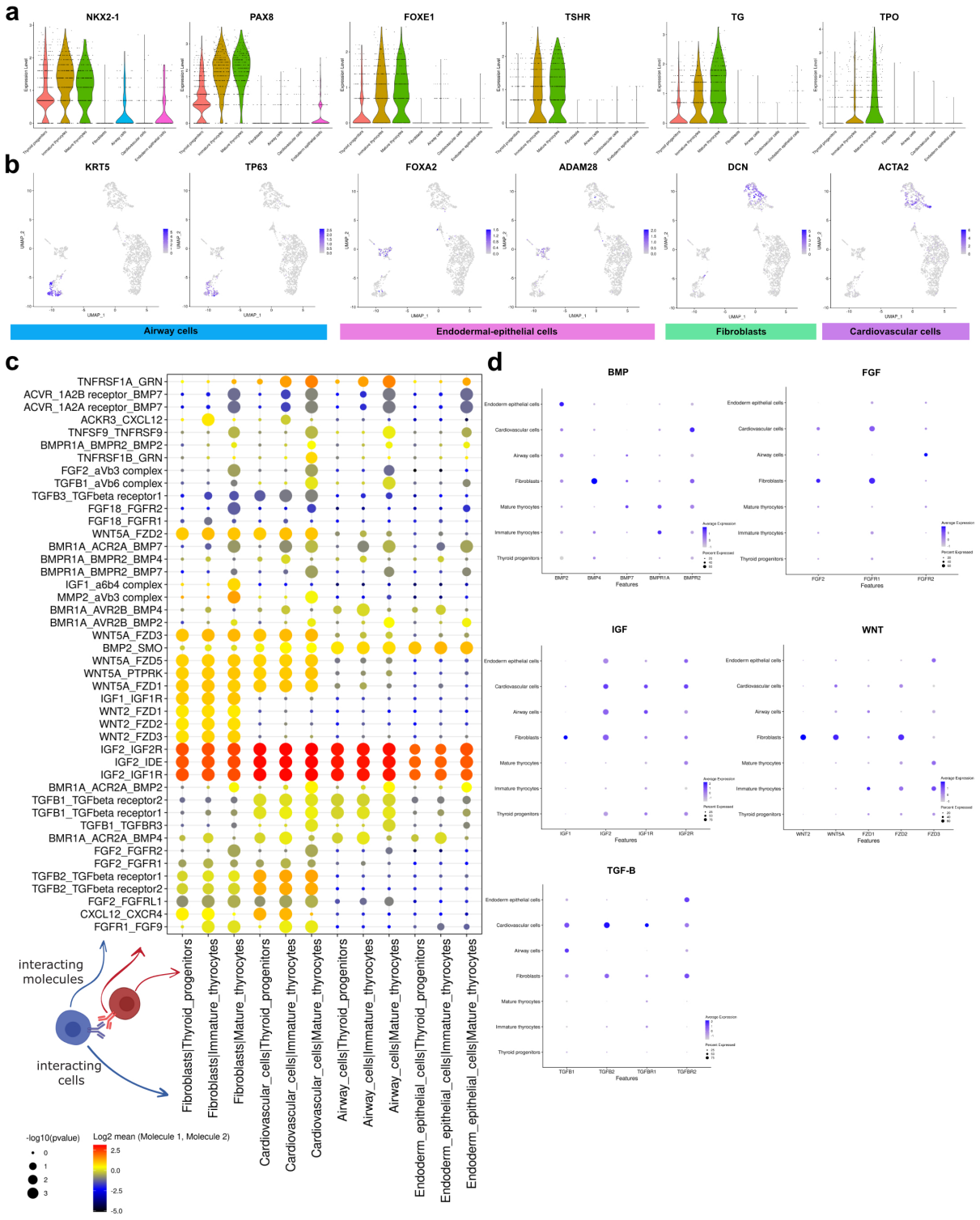


Extended data Fig. 1. Generation, characterization and early differentiation of the NKX21-PAX8 tetracycline-inducible human ESC line. (a) Schematic representation of the previously generated NKX2-1WT/GFP human ES cell line (Goulburn, 2011). (b) NKX21-PAX8 tetracycline-inducible human ESC line was generated by cloning OFRs into the pInducer20 lentivirus vector backbone. (c) Human ESCs showed normal karyotype after genetic manipulations. (d) Modified hESCs showed maintenance of pluripotency by spontaneous differentiation into ectoderm (TUBB3), endoderm (AFP) and mesoderm cells (a-SMA). I *FOXA2* and *SOX17* mRNA levels after activin A (AA) treatment (day 5). (f) Immunostaining shows increase in the percentage of FOXA2+ cells after treatment with AA and (g) induction of NKX2-1 and PAX8 after Dox treatment (day 9). qRT-PCR analysis for exogenous and endogenous *NKX2-1* and *PAX8*, *FOXE1*, *TG* and *TSHR* after Dox stimulation. (i) Gene expression curve of *TG* and exogenous *NKX2-1* and *PAX8* from day 9 to day 16 of the differentiation protocol. Unpaired t-test and Kruskal-Wallis test Multiple comparisons were used for statistical analysis. All analysis were performed using at least three independent experiments. **p<0.01, ***p<0.001. Scale bars, 50 μm.



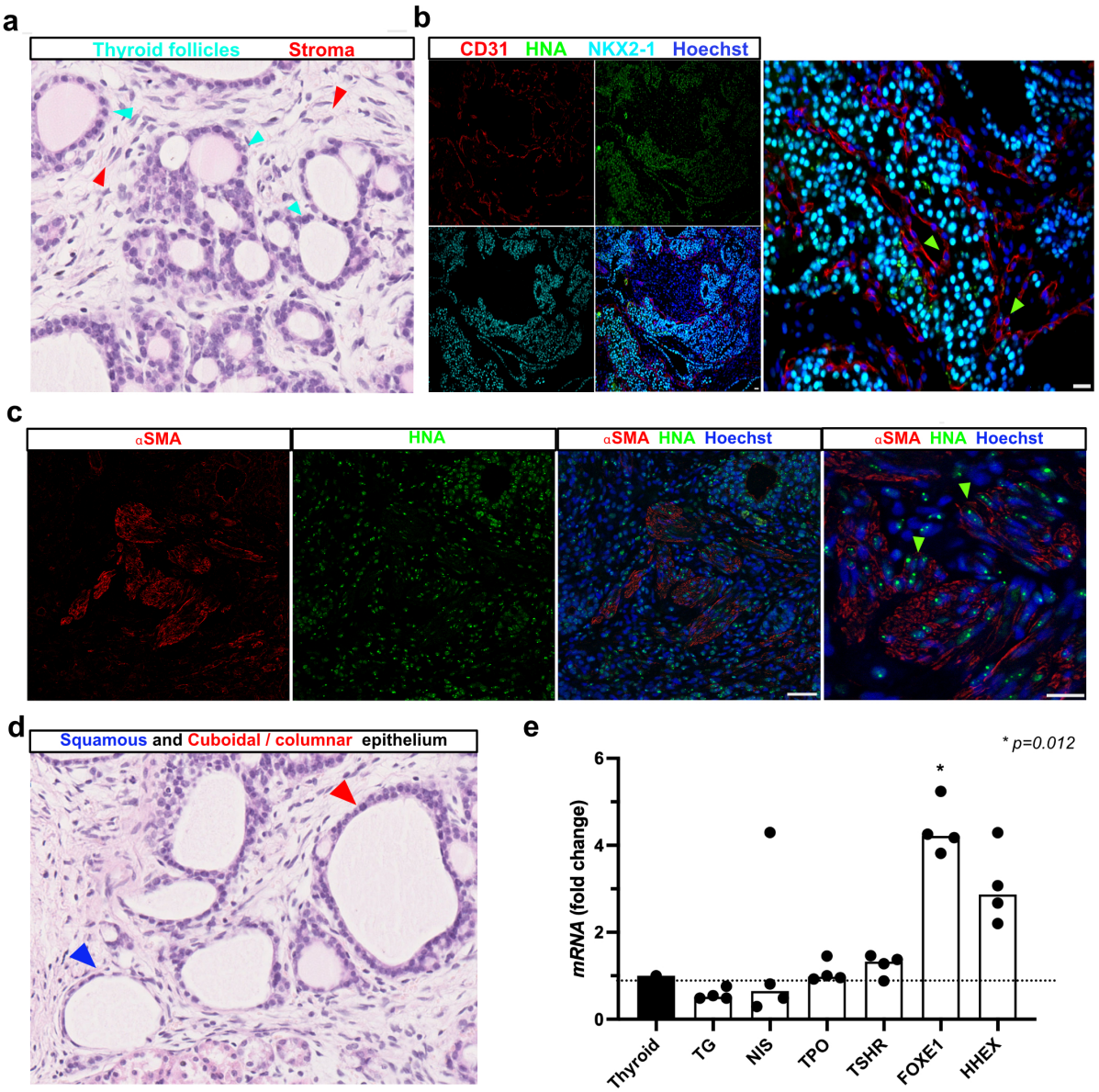
Extended data Fig. 2. Characterization of the proliferation and early differentiation stages of the human thyroid protocol. (a) Proportion of NKX2-1^{GFP+} cells expressing the

proliferation marker KI67 during the differentiation protocol. (b) Heatmap of bulk RNA-Seq expression of proliferation markers in NKX2-1^{GFP+} cells at different stages of the differentiation protocol. Rows represent the marker and columns the specific time point. Color values represent mean expression levels. (c) *NKX2-1*, *TG* and *TSHR* gene expression curve (bulk RNA-Seq data) at different stages of the protocol. (d) NKX2-1 and TG co-staining, at day 28, showed progressive follicular organization, without the monolayer epithelium, but with the appearance of the luminal compartment. (e) qRT-PCR analysis of *PAX8*, *TSHR*, *NIS* /*SLC5A5*, *TG* and *TPO* genes at day 45 compared to -Dox control. (f) Heatmap of bulk RNA-Seq expression of TGFβ signaling markers within NKX2-1^{GFP+} cells by differentiation protocol. (g) NKX2-1 and ZO-1 co-staining, at day 45, shows the single-layered thyroid follicular epithelium and the delimited lumen formed. An unpaired t-test was used for statistical analysis and three independent samples were used for analysis. ****$p<0.0001$. Scale bars, 10 μm.



Extended data Fig. 3. scRNA-Seq clusters characterization and CellPhone-DB heterotypic interaction between thyroid populations and other cells. (a) Violin plots showing expression levels of key thyroid markers between thyroid clusters and other cells. (b) UMAP plots showing the expression of specific differentially expressed markers for non-

835 thyroidal clusters. (c) Diagram showing selected ligand-receptor interactions using
836 CellPhoneDB on the single-cell dataset of human thyroid organoids; P values are indicated by
837 circle size. The color scale shows the Log2 mean values of the average expression level of
838 interacting molecule 1 from cluster 1 and interacting molecule 2 from cluster 2. (d) Dot plot
839 visualization of markers expression from selected relevant interactions data across clusters.
840 Shown are the expression levels of receptors and ligands for BMP, FGF, IGF, WNT and TGFβ
841 pathways. The size of the circles indicates the percentage of expression. The color scale bar
842 indicates the mean values of the average expression levels.
843



Extended data Fig. 4. Histological characterization of transplanted human thyroid tissue. (a) H&E staining shows the presence of multiple thyroid follicles (green arrows) surrounded by stromal cells (red arrows). (b) NKX2-1 and CD31 immunostaining demonstrate the presence of a dense network of small blood vessels in close proximity to the thyroid follicles. CD31+ cells do not express HNA (green arrows), providing clear evidence that the endothelial cells are host-derived. (c) Co-staining of a-SMA and HNA (green arrows) indicates a human origin of the stromal cells. (d) Histological analysis shows the presence of active follicles with cuboidal to weakly columnar epithelium (red arrows) and inactive follicles with flat/scaly cell

853 organization (blue arrows). (e) Gene expression levels of thyroid markers in transplanted tissue
854 (n=4) compared to human thyroid tissue. An unpaired t-test was used for statistical analysis.
855 *p<0.012. Scale bars, 20 µm.

856

857 **Tables**

858

859 **Extended table 1: Human differentiation medium composition**

860

hESC Differentiation Medium	**Stock concentration**	**Final concentration**	**Volume (50 ml)**
DMEM/F12 + Glutamax			38.4 ml
FBS		20% v/v	10 ml
MEM-Non-Essential Amino Acids (MEM-NEAA)	100x	1%	500 µl
Sodium pyruvate	100x	1%	500 µl
P/S	100x	1%	500 µl
2-Mercaptoethanol (in PBS)	7%	0.007%	50 µl
Vitamin C	50 mg/ml		50 µl

861

862 **Extended table 2:** List of primary and secondary antibodies used in the experiments.

Primary antibodies					
Protein Target	***Provider***	***Catalog number***	***Host Species***	***Dilution Flow Cyt.***	***Dilution IF***
AFP	Santa Cruz	sc-8108	Goat		1:100
β-III Tubulin	Eurogentec	MMS-435P-200	Mouse		1:1,000
αSMA	Abcam	ab32575	Rabbit		1:1,000
NKX2-1	Abcam	ab76013	Rabbit		1:500
PAX8	Cell Signaling	59019	Rabbit		1:500
TG	Dako	A0251	Rabbit		1:2,000
TG	Abcam	Ab187378	Mouse		1:250

TPO	Santa Cruz	sc-58432	Mouse		1:100
T4	Biorbyt	orb11479	Goat		1:1,000
T4	Invitrogen	MA5-14716	Mouse		1:100
E-cadherin	BD	610181	Mouse		1:1,000
CD31	R&D	AF3628	Goat		1:100
HNA	Abcam	ab190710	Mouse		1:250
KI67	Abcam	ab15580	Rabbit	1:100	
Secondary antibodies					
Cy3-conjugated	Jackson Immunoresearch	715-165-150	Donkey anti-mouse IgG		1:500
Cy3-conjugated	Jackson Immunoresearch	711-165-152	Donkey anti-rabbit IgG		1:500
Cy3-conjugated	Jackson Immunoresearch	705-165-147	Donkey anti-goat IgG		1:500
Alexa fluor 488-conjugated	Jackson Immunoresearch	715-545-150	Donkey anti-mouse IgG		1:500
Alexa fluor 647-conjugated	Jackson Immunoresearch	715-605-150	Donkey anti-mouse IgG		1:500
Alexa fluor 647-conjugated	Jackson Immunoresearch	711-605-152	Donkey anti-rabbit IgG	1:300	1:500

Extended table 3: List of primers sequences used for qRT-PCR analysis.

Gene name	Primer Forward	Primer Reverse
FOXA2	GGGAGCGGTGAAGATGGA	TCATGTTGCTCACGGAGGAGTA
SOX17	GTGGACCGCACGGAATTTG	CACGTCAGGATAGTTGCAGTAAT
exNXK2-1	TGTCCTGCTCCACCTTGCT	CGCACACCGGCCTTATTCCA
exPAX8	CCTCGGTGCACATGCTTTAC	GAGGTCTGCCATTCACAAAGG
NKX2-1	GCTTCCCCGCCATCTCC	GCCATGTTCTTGCTCAGCTC
PAX8	CGAGCGACTCCCCGGCGAT	GAGGTCTGCCATTCACAA
FOXE1	GCGACAACCCCAAAAAGTGG	GCCCAGTAGCCCTTACC
HHEX	GGACGGTGAACGACTACACGCA	CCAGACGCTTCCTCTCGGCGC
TG	AGACACCTCCTACCTCCCTCA	TCCTTGGACATCGCTTTGGC
TSHR	TGACCTTTCTTACCCAAGCCA	TGCTCTCAAGGACTTACACATCA

TPO	CTGTCACGCTGGTTATGGC	GCTAGAGACACGAGACTCCTCA
NIS/SLC5A5	ATCGCTATGGCCTCAAGTTCC	TCCAGGTACTCGTAGGTGCT
GAPDH	CTATAAATTGAGCCCGCAGCC	TACGACCAAATCCGTTGACTC

865