Dissecting embryonic and extra-embryonic lineage crosstalk with stem cell co-culture

Yulei Wei[1, 2,†], E Zhang[3,†], Leqian Yu[1, 4,†], Baiquan Ci[3], Lei Guo[6], Masahiro Sakurai[1], Shino Takii[7], Jian Liu[3], Daniel A. Schmitz[1], Yi Ding[1], Linfeng Zhan[3], Canbin Zheng[1], Hai-Xi Sun[8], Lin Xu[6], Daiji Okamura[7], Weizhi Ji[3], Tao Tan[3,*], Jun Wu[1,5,9,*]

[1] Department of Molecular Biology, University of Texas Southwestern Medical Center, Dallas, TX 75390, USA

[2] State Key Laboratory of Agrobiotechnology, College of Biological Sciences, China Agricultural University, Beijing 100193, China

[3] State Key Laboratory of Primate Biomedical Research, Institute of Primate Translational Medicine, Kunming University of Science and Technology, Kunming, Yunnan 650500, China

[4] The State Key Laboratory of Stem Cell and Reproductive Biology, Institute of Zoology, Chinese Academy of Sciences, Beijing 100101, China

[5] Hamon Center for Regenerative Science and Medicine, University of Texas Southwestern Medical Center, Dallas, TX 75390, USA

[6] Quantitative Biomedical Research Center, Department of Population and Data Sciences, Peter O'Donnell Jr. School of Public Health, University of Texas Southwestern Medical Center, Dallas, TX 75390

[7] Department of Advanced Bioscience, Graduate School of Agriculture, Kindai University, Nakamachi, Nara 631-8505, Japan

[8] BGI-Beijing, Beijing 102601, China

[9] Cecil H. and Ida Green Center for Reproductive Biology Sciences, University of Texas Southwestern Medical Center, Dallas, TX, USA

[†]These authors contributed equally to this work.

[*]Correspondence to: Tao Tan: tant@lpbr.cn

Jun Wu: Jun2.Wu@UTSouthwestern.edu

SUMMARY

Faithful embryogenesis requires precise coordination between embryonic and extraembryonic

tissues. Although stem cells from embryonic and extraembryonic origins have been generated for

several mammalian species(Bogliotti et al., 2018; Choi et al., 2019; Cui et al., 2019; Evans and

Kaufman, 1981; Kunath et al., 2005; Li et al., 2008; Martin, 1981; Okae et al., 2018; Tanaka et

al., 1998; Thomson et al., 1998; Vandevoort et al., 2007; Vilarino et al., 2020; Yu et al., 2021b;

Zhong et al., 2018), they are grown in different culture conditions with diverse media

composition, which makes it difficult to study cross-lineage communication. Here, by using the

same culture condition that activates FGF, TGF-β and WNT signaling pathways, we derived

stable embryonic stem cells (ESCs), extraembryonic endoderm stem cells (XENs) and

trophoblast stem cells (TSCs) from all three founding tissues of mouse and cynomolgus monkey

blastocysts. This allowed us to establish embryonic and extraembryonic stem cell co-cultures to

dissect lineage crosstalk during early mammalian development. Co-cultures of ESCs and XENs

uncovered a conserved and previously unrecognized growth inhibition of pluripotent cells by

extraembryonic endoderm cells, which is in part mediated through extracellular matrix signaling.

Our study unveils a more universal state of stem cell self-renewal stabilized by activation, as

opposed to inhibition, of developmental signaling pathways. The embryonic and extraembryonic

stem cell co-culture strategy developed here will open new avenues for creating more faithful

embryo models and developing more developmentally relevant differentiation protocols.

INTRODUCTION

In mammals, embryogenesis is accompanied by the establishment and loss of pluripotency, a

transient property enabling embryonic epiblast cells to generate all cells in an adult organism.

Pluripotent epiblast cells can be propogated in vitro in a spectrum of pluripotent stem cell (PSC)

states with different culture conditions (Pera and Rossant, 2021; Wu and Izpisua Belmonte,

2015). PSCs with unique molecular and functional features provide us with invaluable in vitro

models to study early mammalian development with great potential for regenerative medicine.

Despite the potential, however, PSCs exist in the artificial milieu of cell culture, which is vastly

different from the *in vivo* environment. One notable difference is the lack of communication with

extraembryonic cells in cultured PSCs. Extraembryonic tissues play crucial roles in embryo

patterning and size control during early embryogenesis (Rivera-Pérez and Hadjantonakis, 2015;

Shahbazi and Zernicka-Goetz, 2018). Consequently, PSC-only models suffer from several

culture artifacts that potentially limit their potential, e.g., unsynchronized and disorganized

differentiation, and unfettered growth.

To overcome these limitations, for the first time, we succeeded in the derivation of stem cells

from embryonic and extraembryonic tissues using the same condition from both mouse and

cynomolgus monkey blastocysts. This enabled the culture of embryonic and extraembryonic

stem cells in the same environment, and thereby opening the door for dissecting their direct

communication.

RESULTS

A common culture for all blastocyst lineages

We previously reported *de novo* derivation of intermediate embryonic stem cells (ESCs) from

mouse blastocysts by activating F̲GF, T̲GF-β and W̲NT pathways (FTW-mESCs)(Yu *et al.*,

2021b). To enrich the FTW-mESC population, a MEK inhibitor (PD0325901) was added to

suppress the proliferation of extra-embryonic cells(Yu *et al.*, 2021b). Withdrawal of PD0325901

during FTW-mESCs derivation resulted in the co-appearance of epiblast-like cells (ELCs),

trophoblast-like cells (TLCs), and extraembryonic endoderm-like cells (XLCs) in the blastocyst

outgrowth (Figure S1A). After manual picking, separate cultivation, and further passaging in the

FTW condition, stable e̲xtraembryonic e̲ndoderm stem cells (designated as FTW-mXENs),

t̲rophoblast s̲tem c̲ells (designated as FTW-mTSCs), and FTW-mESCs could be derived from a

single mouse blastocyst (Figure 1A and 1B). FTW-mXENs, FTW-mTSCs and FTW-mESCs

expressed extraembryonic endoderm, trophoblast, and epiblast markers, respectively (Figure 1C

and Figure S1B to S1E). Next, we compared FTW-mXENs and FTW-mTSCs with mXENs and

mTSCs in conventional conditions(Chiu et al., 2010; Niakan et al., 2013) (Figure S1F to S1I).

FTW-mTSCs and FTW-mXENs expressed their respective lineage markers at comparable levels

to mTSCs and mXENs, respectively (Figure S1J). Although similar proliferation rates were

observed for mTSCs and FTW-mTSCs, FTW-mXENs exhibited a significantly shorter doubling

time than mXENs (Figure S1K). After random differentiation of FTW-mXENs *in vitro,* several

parietal endoderm (PE) and visceral endoderm (VE) related genes were upregulated(Artus et al.,

2012) (Figure S1L). Following subcutaneous injection into an immunodeficient NOD-SCID

mouse, FTW-mXENs formed a teratoma-like tissue mass (designated as XEN-teratoma) after 3

months (Figure S1M). Immunofluorescence (IF) analysis revealed that within the XEN-teratoma

many cells expressed alpha-fetoprotein (AFP)(Kwon et al., 2006), some cells were GATA6+,

and others stained positive for yolk sac markers FOXA1 and/or COL6A1 (Figure S1N and S1O).

We did not detect T+ (mesoderm) or PAX6+ (ectoderm) cells in the XEN-teratoma (Figure

S1M). For FTW-mTSCs, after random differentiation *in vitro*, multinucleated cells appeared

(Figure S1P) and genes related to trophoblast differentiation were upregulated(Cui *et al.*, 2019)

(Figure S1R). FTW-mTSCs also formed a tissue mass (TSC-teratoma) containing multinucleated

trophoblast giant-cell like cells two weeks after injection into a NOD-SCID mouse (Figure S1Q).

Next, we performed blastocyst injections and found that GFP (green fluorescent protein) or mKO

(monomeric Kusabira-Orange) labeled FTW-mXENs and FTW-mTSCs contributed to chimera

formation in the yolk sac and placenta tissues of mouse conceptuses (E7.5 and E11.5),

respectively (Figure 1D to 1G, Figure S1S and Table S1).

In sum, we discovered a common culture condition could support *de novo* derivation and long-

term culture of embryonic and extraembryonic stem cells from mouse blastocysts.

Transcriptome profiling

We next performed bulk RNA-sequencing (RNA-seq) to examine the global transcriptional

profiles of FTW stem cells and compared them with published datasets from established mouse

embryonic and extraembryonic stem cells(Anderson et al., 2017; Bao et al., 2018; Cruz-Molina

et al., 2017; Cui *et al.*, 2019; Kubaczka et al., 2015; Wu et al., 2015; Wu et al., 2011; Ye et al.,

2018; Zhao et al., 2015; Zhong *et al.*, 2018). We found that FTW-mXENs, FTW-mTSCs and

FTW-mESCs expressed their respective lineage markers and clustered together with stem cells

derived from the same tissue of origin (Figure 2A and Figure S2A, S2B). Based on comparison

with *in vivo* datasets, we found FTW-mESCs, FTW-mTSCs and FTW-mXENs were

transcriptionally most closely related to E5.5 epiblast (EPI), E5.25-E5.5 extraembryonic

ectoderm (ExE)(Cheng et al., 2019) and E5.5 VE(Mohammed et al., 2017), respectively (Figure

S2C and S2D). To resolve the transcriptional states of FTW stem cells, we performed single-cell

RNA-sequencing (scRNA-seq) and compared with published single-cell transcriptomes derived

from E3.5-E6.5 mouse embryos(Nowotschin et al., 2019). Consistent with bulk RNA-seq results,

we found that FTW-mESCs, FTW-mTSCs and FTW-mXENs showed the highest correlation

with E5.5 EPI, E5.5 TE (trophectoderm) and E5.5 PrE (primitive endoderm), respectively

(Figure 2B). Uniform manifold approximation and projection (UMAP) analysis further revealed

FTW stem cells clustered closely with cells from their respective lineages in E5.5 mouse

conceptuses (Figure S2E). To examine the temporal steps of FTW stem cells derivation, in

addition to established FTW stem cell lines (passage 10), we performed scRNA-seq of

blastocysts (day 0) and blastocyst outgrowths (day 8). Our analysis revealed clear segregation of

ELCs, TLCs and ELCs in blastocyst outgrowths (Figure 2C). Slingshot(Street et al., 2018)

pseudotime analysis was performed to delineate differentiation trajectories during derivation.

Interestingly, in blastocyst outgrowths, ELCs have already acquired similar transcriptional states

of stable FTW-mESCs while TLCs and ELCs clustered separately from established FTW-

mTSCs and FTW-mXENs, respectively (Figure 2C). Next, we identified stage specific genes and

enriched Gene Ontology (GO) terms. Notably, several common stage-specific features across all

lineages emerged in our analysis, e.g. blastocysts were enriched with terms related to

modification of DNA, RNA and/or protein, suggesting active gene transcription and translation,

and dynamic signaling activities in these cells; cells in blastocyst outgrowths shared terms

related to actin dynamics, which implicates active cell movement and dynamic changes in cell

shape; established FTW stem cells, on the other hand, are characterized by terms related to

glycolysis and hypoxia, which is indicative of their stabilization in the FTW condition (Figure

2D to 2F).

Taken together, these transcriptomic analyses confirmed lineage identities, revealed temporal

properties and derivation dynamics of FTW-mESCs, FTW-mTSCs and FTW-mXENs.

Cross-lineage stem cell co-cultures

Having FTW-mESCs, FTW-mXENs and FTW-mTSCs derived and maintained in the same

condition enabled us to establish co-cultures to study intercellular communications between

embryonic and extraembryonic lineages (Figure 3A). To this end, we labeled FTW-mESCs with

GFP and subjected them to co-culture with mKO-labeled FTW-mXENs, in the presence or

absence of FTW-mTSCs (unlabeled). Interestingly, after 5 days of co-culture in the FTW

condition, many FTW-mESC colonies were surrounded by FTW-mXENs. These FTW-mESC

colonies appeared smaller and more "domed" when compared to standalone colonies (not in

contact with FTW-mXENs) and FTW-mESC colonies from separate culture (Figure 3B and

Video S1). Of note is that we didn't observe this phenomenon in FTW-mESCs co-cultured with
either FTW-mTSCs or mouse embryonic fibroblasts (Figure 3B). In consistent, we found a
significant reduction of the GFP signal "Area x Intensity/Colony" in FTW-mESCs co-cultured
with FTW-mXENs and FTW-mXENs/FTW-mTSCs (Figure 3C) but not with FTW-mTSCs and
fibroblasts, when compared with separately cultured FTW-mESCs. We also calculated the cell
density (cell number per cm^2) of FTW-mESCs daily in each experimental group. On day 5, a
significantly lower density of FTW-mESCs was found in FTW-ESCs/TSCs/XENs and FTW-
ESCs/XENs groups than in control groups (Figure 3D and Figure S3A). We tested the effects of
different cell plating ratios and found greater reduction in FTW-mESC densities when co-
cultured with more FTW-mXENs in both 2D and 3D (Figure S3B to S3D). This decrease in
FTW-mESC density in co-culture was not due to increased cell apoptosis (Figure S3E and S3F)
or differentiation (Figure S3G) and was dependent on direct contact with FTW-mXENs (Figure
S3H, S3I and Video S1).

Next, we studied whether this growth inhibition phenotype manifested during differentiation. We
injected the same number of FTW-mESCs either alone or together with FTW-mXENs under the
skin of NOD-SCID mice (Figure 3E). Although in both conditions teratomas that contained
tissues from all three germ lineages could be generated (Figure S3J), the average size and weight
of teratomas generated by co-injection were smaller than FTW-mESCs alone (Figure 3F to 3H).
We also tested different ESC:XEN ratios and found in general the more FTW-mXENs were
injected, the smaller the teratomas (Figure S3K). To study whether this growth restriction also
exists between EPI and VE cells, we isolated E6.5-6.75 mouse conceptuses, removed ExE and
ectoplacental cone, and used EPI with or without VE (VE+/-) for *ex vivo* culture (Figure 3I).
Interestingly, the size and total cell number in the VE+ group were significantly smaller than
those in the VE- group (Figure 3J, 3K and Figure S3L), suggesting the proliferation of EPI is
also limited by the VE.

Collectively, we established embryonic and extra-embryonic stem cell co-cultures and identified
a contact-dependent growth restriction of FTW-mESCs by FTW-mXENs, which may reflect an
embryo size control mechanism during early development.

Mechanistic insights

To gain mechanistic insights into the crosstalk among co-cultured FTW stem cells, we performed scRNA-seq analysis (Figure 4A). UMAP analysis showed that cells in co-cultures largely overlapped with separately cultured cells (Figure S4A and S4B). We used the CellChat(Jin et al., 2021) toolkit to infer cell-cell communication. As expected, both the number and strength of cell-cell interactions increased in co-cultures when compared to separate cultures (Figure 4B). Interestingly, a significant proportion of these interactions originated from FTW-mXENs towards the other two cell types, especially FTW-mESCs (Figure 4C). CellChat analysis also predicted several signaling pathways mediating these interactions, which included signaling through extracellular matrix (ECM) proteins such as LAMININ and COLLAGEN (Figure 4D). LAMININ and COLLAGEN are known components of the basement membrane (BM) lining the basal side of the post-implantation EPI, which are in part produced by the VE in mice(Sekiguchi and Yamada, 2018). We next determined whether ECM protein(s) could phenocopy the growth restriction of co-cultured FTW-mESCs. We found supplementation of separately cultured FTW-mESCs with Matrigel (~60% LAMININ, ~30% COLLAGEN IV), LAMININ, or COLLAGEN IV, but not VITRONECTIN could inhibit FTW-mESC growth in a dosage dependent manner (Figure 4E, and Figure S4C, S4D). In consistent, knockout of *Laminin γ1* (*Lamc1*) in FTW-mXENs could partially rescue the growth phenotype of co-cultured FTW-mESCs (Figure 4F and Figure S4E, S4F). As INTEGRIN-β1 plays an important role in ECM protein signaling and is a cell surface receptor for LAMININ-γ1(Barczyk et al., 2010; Molè, 2021; Moore et al., 2014), we generated *integrin β1* (*Itgb1*) knockout FTW-mESCs. We found loss-of-function of *Itgb1*could also mitigate the retarded growth of co-cultured FTW-mESCs (Figure S4G and S4H).

In addition, we studied the transcriptomic differences between separately cultured and co-cultured FTW-mESCs by bulk RNA-seq. Through comparative analysis, we identified 502 differentially expressed genes (DEGs) shared between FTW-mESCs in XENs/ESCs and XENs/TSCs/ESCs co-cultures, when compared to separately cultured FTW-mESCs (Figure S4I and Table S2). Interestingly, the majority of DEGs (492) were down-regulated genes in co-cultured FTW-mESCs. Consistent with their decreased proliferation, the down-regulated DEGs included genes related to cell proliferation and embryo size (e.g., several members of activator protein 1[AP-1] transcription factor complex such as *Fos*, *Fosl1*, *Fosb*, *Batf* among others(Angel et al., 1987; Angel and Karin, 1991; Jochum et al., 2001))(Figure S4J). GO and Bioplanet 2019 analyses of the down-regulated DEGs revealed top enriched terms including extracellular matrix

and structure organization, Interleukin-1 and TGF-beta regulation of extracellular matrix, and β1

integrin cell surface interactions (Figure S4K and S4L). In addition, we found many matrix

metalloproteinases (MMPs) (e.g., *Mmps 2, 3, 9, 10, 12* etc.) were down-regulated in co-cultured

FTW-mESCs (Figure S4M). MMPs have been reported to modulate cell proliferation, migration,

and morphogenesis by degrading ECM proteins(Vu, 2000), and inhibition of MMPs also led to

reduced growth of EPI in vivo and ESCs in vitro(Kyprianou et al., 2020), which are consistent

with our findings.

In sum, these analyses helped gain insights into the crosstalk among co-cultured embryonic and

extraembryonic stem cells and identified ECM signaling as one of the mechanisms mediating the

reduced proliferation of FTW-mESCs by FTW-mXENs (Figure 4G).

Stem cells from monkey blastocysts

By using the FTW condition, we also succeeded in the derivation of several stable extra-

embryonic (FTW-cyXENs and FTW-cyTSCs) and embryonic (FTW-cyESCs, 20% KSR

[knockout serum replacement] was needed) stem cell lines from 7-10 d.p.f. (days post-

fertilization) cynomolgus monkey blastocysts (Figure 5A to 5D, and Table S3). FTW-cyESCs

could also be directly converted from naïve-like ESCs(Fang et al., 2014) through culture

adaptation (data not shown). Once established, FTW-cyXENs, FTW-cyTSCs and FTW-cyESCs

proliferated well, maintained stable colony morphology and normal karyotypes after long-term

culture, expressed hypoblast (HYP), trophoblast, and EPI related genes, respectively (Figure 5E

and Figure S5A to S5D, S5E to S5H, S5L, S5M). Upon random differentiation *in vitro*, FTW-

cyXENs could generate visceral- and yolk-sac-endoderm- (VE/YE-) (FOXA1$^+$ GATA4$^-$) like

cells and extra-embryonic-mesenchyme-cell- (EXMC-) (COL6A1$^+$ GATA4$^-$) like

cells(Nakamura et al., 2016; Niu et al., 2019b) (Figure 5F and S5I). FTW-cyTSCs were capable

of differentiating into extravillous trophoblast (EVT)- like cells and multinucleated

syncytiotrophoblast (SCT)-like cells *in vitro* (Figure 5G and 5H). (Okae *et al.*, 2018) and in

TSC-teratomas (Figure S5J and S5K).

Next, we performed transcriptomic profiling of cynomolgus monkey FTW stem cells. scRNA-

seq analysis revealed that FTW-cyESCs, FTW-cyXENs and FTW-cyTSCs segregated into three

distinct clusters on UMAP and expressed their respective lineage marker genes (Figure 6A and

6B). Bulk RNA-seq analysis helped identify DEGs among FTW-cyESCs, FTW-cyXENs and

FTW-cyTSCs, which were enriched in GO terms including: "Signaling pathways regulating
pluripotency of stem cells" and "VEGF signaling pathway" (FTW-cyESCs); "ECM-receptor
interaction" and "TGF-beta signaling" (FTW-cyXENs); "ECM-receptor interaction" and "Hippo
signaling pathway" (FTW-cyTSCs) (Figure 6C). The result of the Pearson correlation analysis
showed that FTW-cyESCs, FTW-cyXENs and FTW-cyTSCs shared the highest correlation
coefficients with their *in vivo* counterparts (Figure 6D).

Cross-lineage stem cell co-cultures among monkey cells

Next, we investigated whether the growth restriction of FTW-ESCs by FTW-XENs was
conserved in cynomolgus monkeys. To this end, we performed co-culture of FTW-cyESCs with
FTW-cyXENs and/or FTW-cyTSCs. Consistent with mouse findings, we found the growth of
FTW-cyESCs was greatly inhibited by FTW-cyXENs but marginally affected by FTW-cyTSCs
or fibroblasts (Figure 7A, 7B and Figure S6A) To provide mechanistic insights into embryonic
and extra-embryonic lineage crosstalk in cynomolgus monkeys, we performed scRNA-seq
analysis of co-cultures of FTW-cyESCs/FTW-cyXENs (2lines) and FTW-cyESCs/FTW-
cyXENs/FTW-cyTSCs (3lines) using 10x Genomics Chromium, and compared with single cell
transcriptomes derived from separate cultures (Table S4). Through DEG and GO analyses, we
identified several terms, e.g., "Focal adhesion", "Cadherin binding", and "Cell-cell adhesion",
were enriched in co-cultured FTW-cyESCs, FTW-cyXENs and FTW-cyTSCs, respectively,
suggesting more active cell-cell interactions (Figure S6B to S6D). In agreement with mouse
results, CellChat analysis also predicted signaling through ECM proteins, e.g., LAMININ and
COLLAGEN, mediated crosstalk between FTW-cyXENs and FTW-cyESCs (Figure 7C, Figure
S6E and Table S5). To confirm the effect(s) of ECM protein(s), we supplemented Matrigel,
LAMININ, or COLLAGEN IV to separately cultured FTW-cyESCs, and found that each could
phenocopy FTW-cyXENs' inhibitory effect on the growth of FTW-cyESCs in a dosage
dependent manner (Figure 7D and Figure S6F, S6G).

Taken together, these results extended our findings in mice to cynomolgus monkeys and revealed
a conserved mechanism underlying growth inhibition of FTW-ESCs by FTW-XENs.

Cross species comparisons

Embryonic and extraembryonic stem cells from both mice and cynomolgus monkeys derived and
cultured in the same condition gave us a unique opportunity to examine species-conserved and -

divergent features not influenced by different culture parameters. Using the single-cell regulatory
network inference and clustering (SCENIC) pipeline, we first studied the regulatory networks
underlying the maintenance of FTW-ESCs, FTW-XENs and FTW-TSCs in both species. Our
analysis identified several conserved and species-specific transcription factor (TF)-driven
regulons in each stem cell type (Figure S7A to S7C). SCENIC analysis also revealed common
and distinct targets of well-known lineage TFs such as NANOG, SOX17 and GATA3 (Figure
S7A to S7C and Table S6). We next performed cross-species comparison of
intercommunications between lineages, which uncovered both species-conserved (e.g., MK,
LAMININ, COLLAGEN and FN1) and -divergent (e.g., CDH, AGRN and HSPG [mouse]; FGF,
NCAM and BMP [monkey]) signaling crosstalk (Figure S7D). Collectively, these results reveal
interspecies transcriptomic similarities and differences in early embryonic and extraembryonic
cells and their intercommunications, which provide insights into evolutionary convergent and
divergent processes underlying epiblast, hypoblast and trophoblast development across different
species *in vivo*.

DISCUSSION

Most stem cell cultures include pathway inhibitors to suppress differentiation in favor of self-
renewal, e.g., ground state mouse ESC culture (Ying et al., 2008), which often necessitate the
design of new conditions for different stem cell types and different species. By activating
multiple developmental signaling pathways at once, surprisingly, we found several embryonic
(mouse, cynomolgus monkey, and horse) and extraembryonic stem cells (mouse and cynomolgus
monkey) from multiple species could be derived and stably maintained in the same condition
(Wu et al., 2017; Yu *et al.*, 2021b). This signaling "excited" state can potentially be attained in a
variety of stem cell types by striking a balance between differentiation and self-renewal via
switching on a combination of signaling pathways including but not limited to FGF, TGF-β and
WNT pathways used in this study.

The ability to grow embryonic and extraembryonic stem cells in the same culture environment
opens new avenues to dissect the molecular and cellular mechanisms underlying lineage
crosstalk during early mammalian development. Based on FTW stem cell co-cultures, we have
uncovered a previously unrecognized non-cell autonomous control of pluripotent cell
proliferation by extraembryonic endoderm cells, which is in part mediated by the ECM signaling,

in both mice and cynomolgus monkeys. We further revealed a similar overgrowth phenotype in mouse epiblast in the absence of visceral endoderm, providing evidence supporting the in vivo relevance of the observed proliferation restriction. Consistant with this finding, it was previously reported that MMP-mediated basement membrane perforations at the posterior side of the mouse embryo permited growth and primitive-streak extension during peri-gastrulation development (Kyprianou *et al.*, 2020).

Our study identified laminin-integrin signaling contributed to the growth restriction of FTW-mESCs by FTW-mXENs (Figure 4D-4F and Figure S4C-S4F). This is likely due to irregularly distributed matrix materials surrounding integrin β1-deficient FTW-mESCs during co-culture with FTW-mXENs as opposed to a continuous basement membrane layer in WT FTW-mESCs (Moore *et al.*, 2014).A previous study demonstrated that integrin β1-deficient mESCs underwent massive cell death during transition from naive pluripotency toward the formative pluripotency (Molè, 2021). This seemingly contrasts with integrin β1-deficient formative FTW-mESCs (Figures S4G, S4H). A possible explaination is that despite FTW-mESCs exhibited functional formative features including the ability to form blastocyst chimeras and direct responsiveness to primordial germ cell specification, they retain the expression of many naïve pluripotency genes and are recognized as more naïve-like formative PSCs as apposed to more primed-like formative stem (FS) cells (Kinoshita et al., 2021; Yu *et al.*, 2021b). In consistent, the induction of of apoptosis of integrin β1-deficient mESCs during differetnation was found concomitant with the upregulation of OTX2, and OTX2 level was found low in FTW-mESCs (Molè, 2021).

The recent advancements in both extended primate (human and cynomolgus monkey) embryo cultures and stem cell embryo models provide an unprescendented opportunity to study primate early post-implantation development (Deglincerti et al., 2016; Ma et al., 2019; Moris et al., 2020; Niu et al., 2019a; Shahbazi et al., 2016; Yu et al., 2022; Yu et al., 2021a; Zheng et al., 2019). However, the dynamic nature of a developing embryo/embryo model and its cellular complexity make it difficult to dissect the key cell-cell interactions. Here, the establishment of cynomolgus monkey FTW-ESCs, XENs and TSCs under the same condition enables us, for the first time, to delineate cell-cell interactions in a tractable and accessible manner in primates. In future studies, the combination of stem cell co-culture with CRISPR screens will help uncover additional genes

and pathways underlying the crosstalk between extraembryonic and embryonic cells during
embryogenesis in primates.

In sum, the FTW embryonic and extraembryonic stem cells and the co-culture strategy
developed in this study may help provide superior starting cells for generating more robust
integrated stem cell embryo models (Fu et al., 2021) and developing more faithful differentiation
protocols for regenerative medicine.

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AUTHOR CONTRIBUTIONS

J.W. T.T. Y.W. and L.Y. conceptualized the idea, designed, analyzed, interpreted the
experimental results. Y.W. and L.Y. performed most of the mouse cell culture experiments. E.Z.
performed most of the monkey cell culture experiments. B.C. L.G. J.L. H.S. L. X. and T.T.
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EXE in vitro culture experiment. Y.D. helped with data analysis. C.Z. helped with some mouse
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and W.J. supervised the study. Y.W. L.Y. T.T. and J.W. wrote the manuscript with inputs from
all authors.

DECLARATION OF INTERESTS

Y.W., L.Y., T.T. and J.W. are inventors on a patent application (applied through the Board of
Regents of The University of Texas System, application number 63/488,401) entitled "Methods
For the Derivation Culture Of Embryonic and Extra-Embryonic Stem Cells" arising from this
work. The other authors declare no competing interests.

Data availability

A total of thirty-one RNA-seq datasets generated in this study have been deposited in the Gene
Expression Omnibus (GEO) with accession code GSE178459.

Code availability

The sequencing data generated in this study have been deposited to the Gene Expression
Omnibus (GEO) under the accession (GSE178459). They will be made publicly accessible upon
publication.

FIGURE LEGEND

Figure 1. Derivation and characterization of embryonic and extraembryonic stem cells
from mouse blastocyst.

(A) Schematic of derivation of FTW embryonic and extraembryonic stem cell lines from mouse
blastocyst. (B) Representative bright field (BF) images of colonies of FTW-mXENs, FTW-
mTSCs and FTW-mESCs. Scale bar, 100 µm. (C) Representative immunofluorescence (IF)
images of extraembryonic endoderm (GATA6 and SOX17), trophoblast (EOMES and CDX2),
and epiblast (SOX2 and OCT4) lineage markers in FTW-mXENs (top), FTW-mTSCs (middle),
and FTW-mESCs (bottom), respectively. Scale bar, 100 µm. (D) and (F) Representative BF and
fluorescence images showing chimera contribution of GFP-labeled FTW-mXENs (D) and FTW-
mTSCs (F) to E11.5 mouse conceptuses. Scale bar, 1 mm. (E) IF staining of a chimeric yolk sac
membrane for GFP, GATA6 and GATA4. (G) IF staining of a chimeric sagittal placental section

for CK8 and GFP. Different layers of the placenta are delineated by dotted lines. Scale bar, 100

µm. See also Figure S1.

Figure 2. Transcriptomic analyses of mouse FTW stem cells.

(A) UMAP visualization of integrative analysis of FTW-mXENs, FTW-mTSCs, FTW-mESCs

and published datasets of mPSCs(Bao *et al.*, 2018; Cruz-Molina *et al.*, 2017; Wu *et al.*, 2015; Ye

et al., 2018; Zhao *et al.*, 2015), mTSCs(Cui *et al.*, 2019; Kubaczka *et al.*, 2015; Wu *et al.*, 2011)

and mXENs(Anderson *et al.*, 2017; Zhong *et al.*, 2018). (B) Correlation analysis of FTW-

mXENs, FTW-mTSCs and FTW-mXENs with published scRNA-seq dataset of in vivo mouse

embryos from different stages. (C) UMAP analysis of mouse blastocysts, blastocyst outgrowths,

and stable (passage 10) FTW-mESCs, FTW-mXENs and FTW-mTSCs. (D) to (F) Heatmaps and

GO terms analysis of stage-specific (blastocyst, blastocyst outgrowth and stable FTW stem cells)

genes from three lineages during FTW stem cells derivation. See also Figure S2.

Figure 3. Proliferation restriction of FTW-mESCs by FTW-mXENs.

(A) Schematic of the establishment of FTW stem cell co-cultures to study cross-lineage

communications. (B) Representative fluorescence and BF merged images of day 1 to day 5

separately cultured FTW-mESCs (green) and FTW-mESCs co-cultured with FTW-mXENs (red)

and/or FTW-mTSCs (blue arrowheads), or proliferative mouse embryonic fibroblast. Scale bar,

100 µm. (C) Violin plot showing area multiplied by GFP intensity for each FTW-mESC colonies

in day 5 separate and different co-cultures. (D) Growth curves of separate (FTW-mESCs) and

co-cultures (mESCs/mXENs) from days 1 to 5 (mean ± SD, day 1, n = 2, day 2-5, n = 5,

biological replicates).   (E) Schematic of teratoma formation with FTW-mESCs only and FTW-

mESCs co-injected with FTW-mXENs (mESCs:mXENs = 4:1). The same number (1 x 10^6) of

FTW-mESCs were injected in each condition. (F) Images of teratomas generated from FTW-

mESCs injected with (bottom) and without (top) FTW-mXENs. (G) Lengths and widths of

teratomas generated from FTW-mESCs injected with (orange) and without (green) FTW-

mXENs. (H) Weight of teratomas generated from FTW-mESCs injected with (orange) and

without (green) FTW-mXENs. (mean ± SD, n = 5, biological replicates). (I) Schematic of tissue

dissection of E6.5-6.75 mouse conceptus. (J) Representative BF images showing *ex vivo* culture

of EPI+VE (VE+) and EPI (VE-) tissues isolated from E6.5-6.75 mouse conceptuses at indicated

time points. Scale bar, 100 µm. (K) Total cell number of VE+ and VE- tissues after 48 h *ex vivo*

culture (mean ± SD, n = 10, biological replicates). N.S. not significant, ****P-value□<□0.0001,

P-values were calculated using two-tailed Student's t test. See also Figure S3.

Figure 4. Mechanistic insights of growth inhibition.

(A) Schematic of RNA-seq experiments. (B) Bar graphs showing the number (left) and strength

(right) of cell-cell interactions in co-cultures and separate cultures. (C) Circle plots showing the

ratios of number (left) and strength (right) of cell-cell interactions between co-cultured and

separately cultured samples. Red lines, increased interactions; blue lines, decreased interactions.

(D) Heatmaps of outgoing signaling patterns (left) and incoming signaling patterns (right) in co-

cultured mouse FTW stem cells. (E) Violin plot showing area multiplied by GFP intensity for

each FTW-mESC colonies in day 5 separate and co-cultures (mESCs: mXENs = 2:1 or 1:1) as

well as separate cultures supplemented with different ECM proteins. Matrigel_L: 0.5% (v/v),

Matrigel_H: 2% (v/v), Laminin_L: 30 µg/ml, Laminin_H: 120 µg/ml, Collagen_L: 15 µg/ml,

Collagen_H: 60 µg/ml, Vitronectin_L: 5 µg/ml, Vitronectin_H: 30 µg/ml. N.S. not significant. (F)

Violin plot showing area multiplied by GFP intensity for each FTW-mESC colonies in different

conditions. (G) Schematic summary of mechanistic insights of the observed proliferation

inhibition of FTW-mESCs by FTW-mXENs. N.S. not significant, ****P-value□<□0.0001. P-

values were calculated using two-tailed Student's t test. See also Figure S4.

Figure 5. Cynomolgus monkey embryonic and extraembryonic stem cells derivation

(A) Schematic of derivation of FTW embryonic and extra-embryonic stem cell lines from

cynomolgus monkey blastocyst. (B) Representative BF images of a 10 d.p.f monkey blastocyst,

day 12 outgrowth and stable FTW-cyXENs (passage 14). Scale bars, 50 µm. (C) Representative

BF images of a 10 d.p.f monkey blastocyst, day 12 outgrowth and stable FTW-cyTSCs (passage

10). Scale bars, 50 µm. (D) Representative BF images of a 7 d.p.f monkey blastocyst, day 7

outgrowth, FTW-cyESCs, passage 7. Scale bars, 50 µm. (E) Representative IF images of

monkey extra-embryonic endoderm (GATA6 and GATA4), trophoblast (GATA3 and CK7), and

epiblast (OCT4 and SOX2) lineage markers in FTW-cyXENs (top), FTW-cyTSCs (middle), and

FTW-cyESCs (bottom), respectively. Scale bar, 100 µm. (F) Representative IF co-staining

images of COL6A1, FOXA1, and GATA4 in differentiated FTW-cyXENs at day 9. Blue, DAPI.

Scale bars, 100 µm. (G) Representative IF co-staining images of GATA3 with the EVT maker

HLAG in SCT-like cells differentiated from FTW-cyTSCs. (H) Representative IF co-staining

images of GATA3 with the EVT makers HCG and HCGB in EVT-like cells differentiated from

FTW-cyTSCs. See also Figure S5.

Figure 6. Transcriptomic analyses of cynomolgus monkey FTW stem cells.

(A) UMAP analysis of FTW-cyXENs, FTW-cyTSCs and FTW-cyESCs. (B) Bubble plot

showing the expression patterns of lineage makers in FTW-cyXENs, FTW-cyTSCs and FTW-

cyESCs. (C) A heatmap showing the DEGs of FTW-cyESCs, FTW-cyXENs and FTW-cyTSCs,

Selected genes from the DEGs and top two enriched GO terms were shown on the right. (D)

Correlation analysis of FTW-cyXENs, FTW-cyTSCs, FTW-cyESCs and published datasets from

cynomolgus monkey conceptuses.

Figure 7. Cynomolgus monkey embryonic and extraembryonic stem cells co-cultures.

(A) Representative fluorescence and BF merged images of day 1 to day 5 separately cultured

FTW-cyESCs (green) and FTW-mESCs co-cultured with FTW-cyXENs (red arrowheads) and/or

FTW-cyTSCs (blue arrowheads), or proliferative fibroblast. Scale bar, 100 μm. **(B)** Violin plot

showing area multiplied by GFP intensity for each FTW-mESC colonies in different conditions.

(C) Heatmaps of outgoing signaling patterns (left) and incoming signaling patterns (right) in co-

cultured cynomolgus FTW stem cells. **(D)** Violin plot showing area multiplied by GFP intensity

for each FTW-cyESC colonies in day 5 separate and co-cultures (cyESCs: cyXENs = 1:3.5 or

1:7) as well as separate cultures supplemented with different ECM proteins. Matrigel_L: 0.5%

(v/v), Matrigel_H: 2% (v/v), Laminin_L: 2.5 μg/ml, Laminin_H: 10 μg/ml, Collagen_L: 15

μg/ml, Collagen_H: 60 μg/ml. *P-value $<$ 0.05, ****P-value $<$ 0.0001. P-values were

calculated using two-tailed Student's t test. See also Figure S6.

SUPPLEMENTAL INFORMATION

Figure S1. Derivation, characterization of FTW-mXENs, FTW-mTSCs and FTW-mESCs

and developmental potential of FTW-mXENs and FTW-mTSCs.

Figure S2. Transcriptomic analyses of mouse FTW stem cells.

Figure S3. Proliferation restriction of FTW-mESCs by FTW-mXENs.

Figure S4. Mechanistic insights of growth inhibition and transcriptomic analyses of co-
cultured FTW stem cells.

Figure S5. Derivation and characterization of FTW-cyXENs, FTW-cyTSCs and FTW-
cyESCs.

Figure S6. Lineage crosstalk among co-cultured cynomolgus monkey FTW stem cells.

Figure S7. Cross-species comparison.

METHOD DETAILS

Mice.

C57BL/6 and CD-1 (ICR) mice were purchased from Charles River or Envigo (Harlen). NOD-
SCID (NOD.CB17-$Prkdc^{scid}$/J) mice were purchased from the Jackson Lab. Mice were housed in
12-hr light/12-hr dark cycle at 22.1–22.3°C and 33–44% humidity. All procedures related to
animals were performed in accordance with the ethical guidelines of the University of Texas
Southwestern Medical Center. The animal protocol was reviewed and approved by the UT
Southwestern Institutional Animal Care and Use Committee (IACUC) [Protocol #2018-102430].
All experiments followed the 2021 Guidelines for Stem Cell Research and Clinical Translation
released by the International Society for Stem Cell Research (ISSCR). Human-mouse chimeric
studies were reviewed and approved by the UT Southwestern Stem Cell Oversight Committee
(SCRO) [Registration #14].

Cynomolgus Monkeys.

All animals and experimental procedures were approved in 2021 by the ethical committee of the
LPBR and Institute of Primate Translational Medicine and Kunming University of Science and
Technology (IPTM, KUST) , and performed by following the guidelines of the Association for
Assessment and Accreditation of Laboratory Animal Care International (AAALAC) for the
ethical treatment of non-human primates. 2 healthy female cynomolgus monkeys (Macaca
fascicularis), ranging in age from 5 to 8 years with body weights of 4 to 6 kg, were selected for

use in this study. All animals were housed at the State Key Laboratory of Primate Biomedical

Research (LPBR). All cynomolgus monkey embryos related work was conducted at the State

Key Laboratory of Primate Biomedical Research.

Harvesting and culture of mouse embryos.

C57BL/6 female mice (8–10 weeks old) were super ovulated by intraperitoneal (IP) injection

with 5 IU of PMSG (Prospec), followed by IP injection with 5 IU of hCG (Sigma-Aldrich) 48 h

later. After mating with C57BL/6 male mice, embryos at 8-cell to morula stages were harvested

at E2.75 [the presence of a virginal plug was defined as embryonic day 0.5 (E0.5)) in KSOM-

HEPES by flushing oviducts and uterine horns. Embryos were cultured in the mKSOMaa

overnight until blastocyst stage in a humidified atmosphere containing 5% (v/v) CO_2 and 5%

(v/v) O_2 at 37 °C. CD-1 females (8 weeks old or older) in natural estrous cycles were mated with

CD-1 males. Blastocysts were harvested at E3.5 by flushing uterine horns.

Derivation and culture of FTW-mXENs, FTW-mTSCs and FTW-mESCs.

Embryo manipulations were performed under a dissection microscope (Nikon SMZ800N). In

brief, zona pellucidae (ZP) were removed from E3.5 blastocysts by brief treatment with acidic

Tyrode's solution (Millipore MR-004-D). After removing zona pellucidae, embryos were plated

on MEFs in FTW medium [N2B27 basal medium supplemented with FGF2 (20 ng/mL,

Peprotech), Activin-A (20 ng/mL, Peprotech) and CHIR99021 (3 μM, Selleckchem). After 6-8

days in culture, blastocyst outgrowths were passaged using TrypLE and re-seeded onto newly

prepared MEFs. XEN, TSC, and ESC colonies were manually picked for further cultivation.

Established mouse XEN, TSC, and ESC lines were cultured on MEFs plates pre-coated with 0.1%

gelatin in FTW medium. The cells were cultured at 37 °C under 5% CO_2, with daily media

changes. For passaging, the cells were dissociated into single cells using TrypLE Express

(GIBCO) and passaged onto new MEF-coated plates at a split ratio of 1:20 (FTW-mESCs), 1:10

(FTW-mTSCs), and 1:50 (FTW-mXEN) every 3–4 days.

Generation of fluorescent mouse FTW cells.

We used pCAG-IP-mKO or pCAG-IP-eGFP to label FTW-mXENs,FTW-mTSCs, and FTW-

mESCs. In brief, 1–2 μg of pCAG-IP-mKO/eGFP plasmids were transfected into $1 \times 10^6 - 2 \times$

10^6 dissociated single cells using an electroporator (NEPA21, Nepa Gene) following the protocol

recommended by the manufacturer. Then, 0.5–1.0 μg ml^{-1} of puromycin (Invitrogen) was added

to the culture medium 2–3 days after transfection. Drug-resistant colonies were manually picked

between 7 to 14 days and further expanded clonally.

***In vitro* differentiation of FTW-mTSCs and FTW-mXENs.**

FTW-XENs were dissociated into single cells using TrypLE Express and seeded into a 6-well

plate pre-coated with 5 μg/mL Laminin at a density of 2×10^5 cells (mouse XEN) or 5×10^5 cells

(monkey and human XEN) per well in XEN differentiation medium for 9 days, with medium

changes every other day. XEN differentiation medium was prepared using the following: 1:1 (v/v)

mixture of DMEM/F12 and Neurobasal medium, 1X N2 supplement, 1X B27 minus insulin

supplement, 1X GlutaMAX, 1X Nonessential amino acids, 0.1 mM β-mercaptoethanol, 0.5%

Penicillin-Streptomycin, and 10% FBS.

Harvesting and culture of cynomolgus embryos.

Cynomolgus monkey (Macaca fasicularis) ovarian stimulation, oocyte recovery and in vitro

fertilization were performed as previously described(Niu et al., 2014). Briefly, healthy female

cynomolgus monkeys were subjected to follicular stimulation by intramuscular injection of 20

IU of recombinant human follitropin alpha (rhFSH, Gonal F, Merck Serono) for 8 days, then

1,000 IU recombinant human chorionic gonadotropin alpha (rhCG, OVIDREL, Merck Serono)

was injected on day 9. Cumulus-oocyte complexes were collected by laparoscopic follicular

aspiration 32-35 hours following rhCG administration. Follicular contents were placed in

HEPES-buffered Tyrode's albumin lactate pyruvate (TALP) medium containing 0.3% bovine

serum albumin (BSA) (Sigma-Aldrich) at 37°C. Oocytes were stripped of cumulus cells by

pipetting after a brief exposure (<1 min) to hyaluronidase (0.5 mg/mL) in TALP-HEPES to

allow visual selection of nuclear maturity metaphase II (MII; first polar body present) oocytes.

The maturity oocytes were subjected to intracytoplasmic sperm injection (ICSI) immediately and

then cultured in CMRL-1066 medium (Gibco, 11530037) containing 10% FBS at 37°C in 5%

CO_2. Fertilization was confirmed by the presence of the second polar body and two pronuclei.

Zygotes were then cultured in the chemically defined hamster embryo culture medium-9

(HECM-9) containing 10% fetal bovine serum at 37 °C in 5% CO_2 to allow embryo

development. The blastocysts were collected at 7 days post fertilization (d.p.f.). The zona

pellucida of blastocyst was removed by exposure to hyaluronidase from bovine testes (Sigma-

Aldrich) about 30 seconds and embryos were cultured in vitro until 10 days post fertilization.

Derivation and culture of FTW-cyXENs, FTW-cyTSCs, FTW-cyESCs.

For the derivation of FTW-cyXENs and FTW-cyTSCs, 10 d.p.f. cynomolgus monkey embryos

were dissected with a 31-gauge syringe needle and plated into wells of 4-well dish coated with

0.1% gelatin and covered with mitotically inactivated MEF in FTW medium (done the same way

as with mouse). To promote the proliferation of hypoblast, 1% KSR (Thermo Fisher Scientific,

A3181502) and PDGF (10 ng/mL, R&D, 220-BB) were also added(Zhong *et al.*, 2018). After 8-

10 days, XEN-like and TS-like colonies appeared. Single colonies were isolated and then

dissociated by TrypLE (Thermo Fisher Scientific,12604021) for 3 minutes at 37 °C, and

passaged into a well of a 4-well dish. Established FTW-cyXENs and FTW-cyTSCs were

passaged by TrypLE every 6-7 days (monkey) at a split ratio of 1:10 in FTW medium under 20%

O_2 and 5% CO_2 at 37□. To derive FTW-cyESCs(Kang et al., 2018), blastocysts (7 days p.c.)

were plated into a well of 4-well dish coated with 0.1% gelatin and MEFs in FTW cyESC

medium [N2B27 basal medium supplemented with 20% KSR, FGF2 (6 ng/mL, Peprotech),

Activin-A (25 ng/mL, Peprotech) and CHIR99021 (1.5 μM, Selleckchem)] under 5% O_2 and 5%

CO_2. After 8-10 days, the ES-like outgrowths appeared and were dissociated using TrypLE for 3

minutes at 37 °C. The established FTW-cyESCs were cultured in a 6-well plate pre-coated with

0.1% gelatin MEFs in FTW cyESC medium under 20% O_2 and 5% CO_2 at 37□.

In vitro **Differentiation of FTW-cyXENs.**

To induce differentiation, FTW-cyXENs were dissociated into single cells using TrypLE and

seeded into a 6-well plate pre-coated with 5 μg/mL Laminin at a density of 5×10^5 cells per well

and kept in differentiation medium for 9 days with medium changes every other day.

Differentiation medium was prepared as following: 1:1 (v/v) mixture of DMEM/F12 and

Neurobasal medium, 0.5X N2 supplement, 0.5X B27 supplement, 1% GlutaMAX, 1%

Nonessential amino acids, 0.1 mM β-Mercaptoethanol, 1% Penicillin-Streptomycin, and 10%

FBS.

In vitro **Differentiation of FTW-cyTSCs.**

FTW-cyTSCs were differentiated into ST and EVT as the described with human cells(Okae *et al.*,

2018). For the induction of EVT cells, FTW-cyTSCs were dissociated into single cells in a 6-

well plate pre-coated with 1 mg/ml Collagen-IV at a density of 1×10^5 cells per well and

cultured with 3 mL of EVT medium (DMEM/F12 supplemented with 1% Penicillin-

Streptomycin, 0.3% BSA, 4% KnockOut Serum Replacement ,0.1 mM β-Mercaptoethanol ,1%

ITS-X supplement, 100 ng/ml NRG1, 2.5 mM Y27632, 7.5 mM A83-01). 2% Matrigel was

added to the medium on the first day. At day 3, the medium was changed to EVT medium with 0.5% Matrigel, but without NRG1. At day 6, the medium was replaced with EVT medium with 0.5% Matrigel, but without NRG1 and KSR, and cells were cultured for an additional two days. For differentiation of ST (2D) cells, FTW-cyTSCs were dissociated in a 6-well plate pre-coated with 2.5 mg/ml Collagen-IV at a density of 2×10^5 cells per well and cultured in 3 mL of ST(2D) medium (DMEM/F12 supplemented with 0.1 mM β-Mercaptoethanol, 1% Penicillin-Streptomycin, 4% KSR, 0.3% BSA, 1% ITS-X supplement, 2.5 mM Y27632 and 2 mM Forskolin). The medium was replaced on day 3, and the cells were analyzed on day 6. For the differentiation of ST (3D) cells, 2×10^5 FTW-cyTSCs were seeded in a 3.5 cm Petri dish and cultured with 3 mL of ST (3D) medium (DMEM/F12 supplemented with 0.1 mM β-Mercaptoethanol, 1% Penicillin-Streptomycin, 4% KSR, 0.3% BSA, 1% ITS-X supplement, 2 mM Forskolin, 50 ng/ml EGF, and 2.5 mM Y27632]. An equal amount of fresh ST (3D) medium was added at day 3. The cells were passed through a 40 μm mesh filter to remove dead cells and debris at day 6.

RT-PCR and qRT-PCR Analysis.

Total RNA was isolated using the RNeasy Mini Kit (QIAGEN) following the manufacturer's instructions. Contaminating genomic DNA was removed by RNase-Free DNase Set (QIAGEN). RNA concentrations were measured on a spectrophotometer (DS-11+, DeNovix). cDNA was synthesized with iScript Reverse Transcription Supermix kit (BIO-RAD) and amplified with PrimeSTAR GXL DNA Polymerase (TaKaRa) or with SYBR Green PCR Master Mix (Thermo Fisher Scientific) on a Touch Thermal Cycler Real-Time PCR system (C1000, BIO-RAD). GAPDH was used as an internal normalization control. All primers used in this study were listed in Table S7.

Cell population doubling time.

The cell population doubling time was calculated using the doubling time online calculator (http://www.doubling-time.com/compute.php?lang=en).

Cell Growth Curve.

FTW-cyXENs, FTW-cyTSCs and FTW-cyESCs's (1×10^5) were seeded onto 6-well plates coated with MEF in FTW medium, with media changes every day. Cells were harvested by TrypLE Express at the indicated time points, depleted of MEFs by plating the cell suspension

617 onto 0.5% gelatin-coated plates for 30 minutes, and growth curves were generated by manual

618 cell counting.

Teratoma formation.

For FTW-mTSC and FTW-mXEN teratomas, a total of 5×10^6 cells were resuspended in 100 μL

of DMEM-Matrigel solution (1:1) and injected subcutaneously into 10-week-old

immunodeficient NOD-SCID mice. After 2 weeks, FTW-mTSC teratomas were dissected and

fixed with PBS containing 4% formaldehyde. After 3 months, FTW-mXEN teratomas were

dissected and fixed with PBS containing 4% formaldehyde. For cyTSC teratomas, a total of $1 \times$

10^7 cells were resuspended in 100 μL of DMEM-Matrigel solution (1:1) and injected

subcutaneously into 10-week-old immunodeficient NOD-SCID mice. After 7 days, FTW-mTSC

teratomas were dissected and fixed with PBS containing 4% formaldehyde. For co-culture

experiments, the FTW-mESC only group was injected with 1×10^6 FTW-mESCs, and the co-

culture group was injected with 1×10^6 FTW-mESCs and 2.5×10^5 FTW-mXENs. After one

month, teratomas were dissected, weighed, and then fixed. Paraffin-embedded teratomas were

sliced and stained with hematoxylin and eosin. Teratomas were formed using the following cell

numbers: 1×10^6 FTW-mESCs only, or 1×10^6 FTW-mESCs plus 1.25×10^5 (8:1), 2.5×10^5

(4:1), 5×10^5 (2:1), 1×10^6 (1:1), 2×10^6 (1:2) FTW-mXENs. After one month , teratomas were

dissected, weighed, and fixed.

Immunostaining.

Samples were fixed in 4% PFA for 15 min, washed three times with PBS and permeabilized with

0.5% Triton X-100 in PBS for 30 min at room temperature. Cells were then blocked with

blocking buffer [5% (w/v) BSA; and 0.1% (v/v) Tween 20 in PBS] for 1 h and incubated with

the primary antibodies (Table S7) diluted in blocking buffer at room temperature for 2 h or at

4°C overnight. After three washes with PBST (PBS plus 0.1% Tween 20), the cells were

incubated with corresponding secondary antibodies (1:300 diluted, Table S7) in blocking buffer

at room temperature for 1 h. After additional three times PBST washes, cells were counterstained

with 300 nM DAPI solution at room temperature for 20 min before mounting. Samples were

imaged using a fluorescence (Echo Laboratories, CA) or a confocal microscope (A1R, Nikon).

Flow Cytometry.

Cells were dissociated with TrypLE Express at 37 °C for 5 min. Then, the cells were fixed in 4%

PFA at room temperature for 30 min and permeabilized with 0.5% (v/v) Triton X□100 at room

temperature for 30 min. The cells were then incubated in the primary antibody (Table S7)
solution for 30 min and then the secondary antibody solution for 30 min at room temperature.
Samples stained with only secondary antibodies were used as the negative controls. Between
each step, the samples were washed twice with PBS containing 2% FBS. Finally, the stained
cells were suspended in PBS containing 2% FBS and analyzed by flow cytometry (FACScalibur
system, BD).

Blastocyst injection of FTW-mXENs and mouse FTW-mTSCs.

FTW-mXEN injection into mouse blastocysts was performed as described previously(Yu *et al.*,
2021b) with slight modifications. Briefly, single cell suspensions of mouse and human FTW-
mXENs were added to a 40 μL droplet of KSOM-HEPES containing the blastocysts and placed
on an inverted microscope (Nikon) fitted with micromanipulators (Narishige). Individual cells
were collected into a micropipette with 15–20 μm internal diameter (ID), and a Piezo Micro
Manipulator (Prime Tech) was used to create a hole in the zona pellucida and trophectoderm
layer of mouse blastocysts. 10-12 (FTW-mXEN/ FTW-mTSCs) cells were introduced into the
blastocoel. After microinjection, the blastocysts were cultured in mKSOMaa. For mouse embryo
transfer, 8–12 weeks old ICR female mice were used as surrogates and were mated with
vasectomized ICR male mice to induce pseudopregnancy. Ketamine (30 mg/ml) / Xylazine (4
mg/mL) and Buprenorphine (1 mg/mL) were used in surgery for maintaining anesthesia and
relieving pain. Injected blastocysts were transferred to the surrogate uterine at E2.5. 14–30
blastocysts were transferred within 20–30 min per surrogate.

Immunostaining and imaging of chimeric embryos.

At E7.5 or E11.5, surrogates were euthanized, and embryos were isolated. Embryos were
dissected and checked for fluorescence using zeiss Axio Zoom.V16 fluorescence stereo zoom
microscope equipped with a Plan-Neofluar Z 1.0x/0.25 (FWD 56 mm) objective and Axiocam
503 monochromatic camera. Embryos were fixed in 4% paraformaldehyde and incubated at 4°C
for 30 min (E7.5 embryos) or overnight (E11.5 embryos). After overnight cryoprotection in 30%
sucrose solution (Fisher), the embryos were embedded in Polyfreeze Tissue freezing medium
(Polyscience, Inc) and frozen on dry ice. Sections (10 μm thick) of the different embryos were
cut on a Leica cryostat (Leica CM1950). For immunostaining, 10 mM citrate buffer (0.05%
Tween 20 based) was used for antigen retrieval. The primary antibodies used were summarized
in Table S7. After washing with TBST three times, the cells were incubated with corresponding

secondary antibodies in blocking buffer at room temperature for 1 hour. Samples were
counterstained with 300 nM DAPI solution at room temperature for 20 min and washed with
PBST at least three times. Finally, slides were imaged using a fluorescence microscope (Echo
Laboratories, CA).

Mouse cell-cell co-culture assay.

FTW-mESCs-eGFP, FTW-mTSCs-WT, and FTW-mXENs-mKO/WT were seeded onto MEF-
coated plates either cultured separately or mixed at different ratios for co-cultures. The seeding
ratio and density were empirically tested and decided on the basis of cell growth rate. A starting
number of FTW-mESCs-eGFP (1.5×10^4 cells), FTW-mTSCs-WT (3×10^4 cells, and FTW-
mXENs-mKO (7.5×10^3 cells) were decided on for most of the cell-cell co-culture assays.
During co-culture experiments, cells were cultured in FTW medium on MEFs for 5 days and the
following analyses were performed. For co-culture experiments with various different cell ratios,
FTW-mESCs-eGFP were seeded at a fixed cell number (1.5×10^4 cells per well) and with
varying numbers of FTW-mTSCs-WT and/or FTW-mXENs-WT.

For 3D co-culture, AggreWell™800 was used to form Embryoid bodies (EBs). For separate
culture experiments, FTW-mESCs-eGFP were seeded into an AggreWell™800 with 2.4×10^5
cells per well (800 cells per microwell), and for co-culture experiments, 2.4×10^5 cells FTW-
mESCs-eGFP and 1.2×10^5 FTW-mXENs-WT were added per well (400 cells per microwell).
The next day, EBs were transferred into 6-well low-attachment plates for further culture. Media
was changed every day for 4 days using FTW medium. For 3D co-culture experiments with
different ratios, FTW-mESCs-eGFP were seeded at the fixed density of 2.4×10^5 cells per well
and with varying densities of FTW-mXENs-WT.

For the differentiation co-culture experiments, FTW-mESCs-eGFP and FTW-mXENs-mKO
were seeded, and the medium was switched to differentiation medium containing DMEM/F12
supplemented with 10% fetal bovine serum (FBS) the next day. On day 5, the number of FTW-
mESCs-eGFP cells was counted.

Transwell culture assay.

For transwell co-culture experiments, Millipore Transwell 0.4 μm PET hanging inserts (Millicell,
MCH12H48) were used by placing them into 12-well plates. MEFs were coated on the top/
bottom well. For separate culture groups, FTW-mESCs-eGFP (5000 cells) were seeded on the
bottom wells, but not the top insert. For co-culture groups, FTW-mESCs-eGFP (5000 cells) and

FTW-mXENs-WT (2500 cells) were seeded on the bottom and top insert of the wells,
respectively. Half of the medium was changed every day and cell numbers were counted on day
5.

Mouse ECM protein inhibition assay.

Mouse FTW-mESC-GFP cells were passaged using TrypLE and seeded in a well of 6-well plate
at 1.5×10^4 cells in FTW cyESC medium under 20% O_2 and 5% CO_2 at 37□. After 4 hours, the
ECM protein mixtures (Matrigel_L: 0.5% (v/v), Matrigel_H: 2% (v/v), Laminin_L: 30 µg/ml,
Laminin_H: 120 µg/ml, Collagen_L:15 µg/ml, Collagen_H:60 µg/ml, Vitronectin_L: 5 µg/ml,
Vitronectin_H: 30 µg/ml) were directly added into the culture medium every day for 5 days.
Medium and ECM proteins were changed every day.

Monkey cell-cell co-culture assay.

FTW-cyESCs-GFP, FTW-cyTSCs-WT, and FTW-cyXENs-mKO or WT were seeded onto
MEF-coated plates and mixed at different ratios for co-culture experiments. The seeding ratios
and densities were empirically tested and decided on the basis of cell growth rate. These numbers
were: FTW-cyESCs-GFP (5×10^4 cells), FTW-cyTSCs-WT (30×10^4 cells, and FTW-cyXENs-
mKO/WT (35×10^4 cells). During co-culture experiments, cells were cultured in MEF-coated
plates in FTW cyESC medium for 5 days.

Monkey ECM protein inhibition assay.

Monkey FTW-cyESC-GFP cells were passaged by treatment with TrypLE and 5×10^4 cells were
seeded into a well of 6-well plate in FTW medium under 20% O_2 and 5% CO_2 at 37□. After 4
hours, ECM mixtures were added (Matrigel: 0.5%, 2%; Laminin: 2.5µg/ml, 10µg/ml;
Collagen□:15 µg/ml, 60 µg/ml) directly added into the culture medium every day for 5 days.
Medium and ECM proteins were changed every day.

Total FTW-mESCs/cyESCs number counting.

For all of the co-culture experiments, total ES cell numbers were quantified in the following
manner. Cells were dissociated into single cells using TrypLE Express at 37 °C for 4 min, and
the total number of live cells were counted. Next, the relative percentage of eGFP+ FTW-ESCs-
eGFP were determined using an LSR II Flow Cytometer (BD Bioscience). Total ES cell number
(tN) for each group in both the co-cultured and separate culture conditions were determined by
multiplying total cell volume (V) with cell concentration (CC) and percentage of eGFP+ cells (P).

tN = V × CC × P. Cell density (cells cm^{-2}) was calculated by dividing the total cell number by

the surface area.

Colony Size and intensity analysis.

All of the co-culture experiments involving colony size and intensity were analyzed in the

following method. On day 5 of co-culture, fluorescently labeled cells were imaged with a Leica

Microsystem DMi8 microscope using Leica Application Suite X software for analysis. The

images were taken randomly by the software in a fixed area for each well and A Fiji pipeline was

used to quantify the size and intensity of the ESCs colonies. Briefly, images are preprocessed

with median filters to filter out noise and small debris, binary images are then created through

Otsu thresholding, and watershed was applied to separate merged clones. The quantification was

implemented with the Analyze Particles function of Fiji based on the binary images created

earlier. The average ESC colony Pixels (P) for each group in co-cultures and separate cultures

were determined by multiplying colony Size (A) with colony intensity (I). P = A × I. For mouse

cell experiments, there were three independent biological replicates for each group and 3 images

for each sample. All of the colonies from 9 images were analyzed. For monkey cell experiments,

10 images were taken randomly and all of the colonies were analyzed in the 10 images.

E6.5 epiblasts in-vitro cultivation assay with or without visceral endoderm.

To obtain embryos, ICR females were mated with males from ICR (Charles River Laboratories)

in the afternoon, and the presence of vaginal plugs was checked the next morning. The day on

which a plug was found was considered to be E0.5. Both male and female mice were used at

ages between 6 to 25 weeks. All the animal experiments were performed under the ethical

guidelines of the Kindai University, and animal protocols were reviewed and approved by the

Kindai University Animal Care and Use Committee. The developmental stage of embryos is

critical for adapting the cultivation of isolated epiblast to an STO-conditioned medium. The

isolated epiblasts before the onset of gastrulation collapsed in culture, while those after at onset

of gastrulation were stable for growth in an STO-conditioned medium and were applicable for

further experiments. The embryos at E6.5-6.75 were surgically isolated in cold DMEM

supplemented with 10% fetal calf serum (FCS, BioWest), and whole epiblasts were isolated by

the mechanical removal of Reichert's membrane, extra-embryonic ectoderm as well as visceral

endoderm, depending on the cases, using fine forceps and a tungsten needle. The isolated

epiblasts with or without visceral endoderm were plated into Nunclon Sphera-treated, 96-well U-

shaped-bottom microplate (174925, Thermo Scientific) in STO-conditioned medium. The STO-

conditioned medium was prepared as follows. Dulbecco's Modified Eagle's Medium (DMEM,

SIGMA) supplemented with 10% fetal bovine serum (FBS, Gibco) and 1% Penicillin-

Streptomycin (10,000 U/mL, Gibco) was used to culture Mitomycin-C inactivated STO feeders

for 2 days. After 48 hours, cultured epiblast outgrowths including visceral endoderm in the case

were dissociated with TrypLE (Gibco, 12604013), and the total cell number was counted.

Bulk RNA-sequencing.

RNA extraction was performed using an RNeasy Mini Kit (QIAGEN) using DNase treatment

(QIAGEN). RNA was analyzed using a 2100 Bioanalyzer (Aglient Technologies). (Transcripts

per Kilobase Million). For monkey cells, RNA was extracted with Trizol Reagent (15596026,

Invitrogen). The RNA (~50 ng) reverse transcription reaction and amplification were performed

using SuperScript II (18064-071, Invitrogen), and KAPA HiFi HotStart Ready Mix (KK2602,

KAPA). The cDNA was analyzed using a 2100 Bioanalyzer (Aglient Technologies). The RNA

Library was generated using TruePrep DNA Library Prep Kit V2 for Illumina (TD501, Vazyme),

then the library was adapted for sequencing on an Illmina NovaSeq 6000 platform (sequenced by

Annoroad).

Pre-processing of raw RNA-seq data.

All reads were mapped to the mouse (GRCm38/mm10), human (GRCh38/hg38), and rhesus

macaque genome (Mmul_10/rheMac10) using hisat2 (version 2.2.1) with default settings.

FeatureCoumt (version 2.0.1) was used to estimate read counts. Stringtie (version 2.1.4) was

used to estimate fragments per kilobase of exon per million fragments mapped (FPKM) and

transcripts per kilobase of exon model per million mapped reads (TPM) values according to a

previous report(Kovaka et al., 2019), genes with an FPKM value ≥3 were considered as

expressed.

Comparison analysis with published available datasets.

The previously published datasets including mouse(Bao *et al.*, 2018; Cruz-Molina *et al.*, 2017;

Cui *et al.*, 2019; Kubaczka *et al.*, 2015; Mohammed *et al.*, 2017; Wu *et al.*, 2015; Wu *et al.*,

2011; Ye *et al.*, 2018; Zhao *et al.*, 2015; Zhong *et al.*, 2018), human(Linneberg-Agerholm et al.,

2019; Xiang et al., 2020; Zhou et al., 2019) and monkey(Ma *et al.*, 2019; Nakamura *et al.*, 2016;

Niu *et al.*, 2019b) embryonic single-cell RNA sequencing and mouse cell lines (nEND)

microarray datasets(Anderson *et al.*, 2017) were obtained from GEO repository (NCBI) and

incorporated into our analysis. The expression levels of scRNA-seq data were transformed into

log2(TPM + 1), and those of microarray data were transformed into log2(intensity).

Principal components analysis (PCA).

805   The principal component analysis (PCA) was performed using the prcomp function without

806   scaling. The DEGs were defined as genes exhibiting more than twofold changes between the

807   samples (P < 0.005) and the sum of the expression level of every gene was log2(TPM+1) > 0

808   with the variance > 0.

Similarities inference between cells.

We selected the union of the top 2000 genes of highest variance for our dataset and the published

dataset and calculated 20 canonical correlates (CCs) with diagonal CCA. After running CCA, the

first 10 CCs were used for t-SNE visualization. The homology cell types were co-clustered in the

same CCA cluster. Then, the correlation analysis was employed to detect the correspondence of

cell subtype for our cells and the previous published embryonic cells by using expression matrix

of 200 high variable genes that contributed to the first 10 CCs.

Differential expression and GO and KEGG pathway analysis.

Differentially expressed genes (DEGs) among clusters were detected by the Seurat function

"Find All Markers". Heatmaps showing the expression distribution of marker genes of cell

clusters were created by pheatmap R package. We used the functions enrichKEGG and

enrichGO in clusterProfiler R package(Yu et al., 2012) to perform KEGG pathways(Kanehisa et

al., 2019) and Gene Ontology (GO) biological processes enrichment analysis. A pathway or

process with a P value ≤ 0.05 was considered to be significantly enriched. The enriched

pathways and processes were visualized with the ''ggplot'' function in the ggplot2 package in R.

Single cell samples preparation.

Mouse blastocysts were collected at E3.5 and the zona pellucida removed by Tyler's buffer as

described previously(Yu *et al.*, 2021b). After removing the zona, blastocysts were washed in

PBS/PVA two times. Digestion was performed in TrypLE Express for 10 minutes at 37 □, and

cell clumps were cut up by mouth glass pipettes beginning with a larger size (50 um diameter) to

a smaller size (20 um diameter). The totally digestion time was around 40-50 minutes. For the

FTW-derive-day 8 outgrowth samples, blastocysts were collected and plated onto MEF-coated

plates in FTW medium for 8 days, and then the outgrowth area were picked and dissociated. For

the established FTW cell lines, all the cells were dissociated with TripLE Express for 3-5

minutes at 37 □.

scRNA-seq library preparing and sequencing.

Single cell suspensions were diluted at a concentration of 1100 cells/µL in 0.04% bovine serum

albumin (BSA)/PBS for loading into 10X Chromium Single Cell G Chips (for mouse blastocysts,

all the of the cells were loaded into the chip). Single cell libraries were prepared using the

Chromium Single Cell 3' Reagent Kit v3.1 (10X Genomics, Pleasanton, CA) following the

manufacturer's protocol. Briefly, single cells were partitioned into Gel beads in EMulsion

(GEMs) in the GemCode instrument followed by cell lysis and barcoded reverse transcription of

RNA, amplification, shearing and 5' adaptor and sample index attachment. Libraries were

sequenced on the Illumina NovaSeq 6000 platform.

scRNA-seq data analysis.

Single-cell gene expression count matrix was constructed with Cell Ranger (v6.0.0). The

subsequent analyses were performed using the Seurat package (v4.6.0) (Hao et al., 2021). For

each dataset, transcription noise cells were removed by a series of criteria, including minimal

expression of 200 genes per cell, mitochondrial read percentage $<$ 20%, ribosomal read

percentage $> 5\%$, as well as specific minimal/maximal number of genes and maximal reads for

each dataset. For the monkey, after stringent quality filtering, we generated 35987 single cell

transcriptomes with a median unique molecular identifier (UMI) of 22277 and gene number of

5436. Cells passed quality control were merged and normalized using Seurat's SCT method.

Datasets from different sources were integrated using Seurat's CCA method. The UMAP

dimensional reduction was performed using the first 30 PCs from the PCA analysis. Cells were

then clustered using the FindClusters function in Seurat package. Cell identities were annotated

based on the expression of cell marker genes. To examine the correlation among cell clusters, we

first performed PCA analysis for each cell cluster and then carried out correlation analysis using

the PC1s extracted from the cell clusters.

Cell clustering by nonlinear dimensional reduction.

To remove the influence of different experimental conditions on the samples, batch effect

correction was carried out. Briefly, following the standard processing steps, including use of

"SelectIntegrationFeatures" function to select 2,000 feature genes, "FindIntegrationAnchors"

function to find a set of anchors between different samples, "IntegrateData" function to integrate

data, "RunPCA" and "RunUMAP" function select 30 PCs dimensionality reduction, "DimPlot"

function to graphs the output of a dimensional reduction technique on a 2D scatter plot. The

Seurat package was applied to perform cell clustering analysis based on TPM expression values,

and only the genes with an expression level greater than 5 were included for further analysis.

Then uniform manifold approximation and projection (UMAP) were applied for visualization.

First, ''FindIntegrationAnchors'' function took these objects as input with parameters as

''k.anchor = 5, anchor.features = 2000'' and returned an anchor object. Then, ''IntegrateData''

function used the anchor object to integrate all data- sets with the default parameter. Finally, the

top-10/30 principal components (PCs) were used for clustering (with a resolution of 1) by Seurat.

Pseudotime trajectory analysis.

Slingshot(Street *et al.*, 2018) was used to determine cell Pseudotime trajectories. Frist, the object

that determines the cell type is passed into the "SingleCellExperiment" sim object. Then use a

"Rtsne" function to dimensionality reduction (dims = 2, perplexity = 10, pca = TURE, pca_scale

= FALSE, normalize = FALSE). Slingshot analysis was then performed on the diffusion map to

determine per-cell pseudotime estimates and mapped back to the UMAP embedding.

Gene regulatory networks.

Single cell regulatory network inference and clustering (SCENIC) (Aibar et al., 2017) has been

used to infer gene regulatory networks based on single cell expression profiles and identify cell

states, providing important biological insights into the mechanism of cell heterogeneity. To

identify important transcriptional regulation during cell development, we used pySCENIC

grn/ctx/aucell of the Python module tool pySCENIC to obtain core regulatory TF. The workflow

first describes the input single-cell expression abundance profile matrix and applies a per-target

regression method (GRNBoost2) to infer co-expression modules from which indirect targets are

pruned based on cis-regulatory motif discovery (cisTarget). Subsequently, the activity of these

regulatory factors was quantified using aucells, and the regulatory factor activity score (RAS)

was obtained by enrichment and scoring the target genes of the regulatory factors. The regulator

specificity score (RSS) was calculated based on Jensen-Shannon divergence (JS) to determine

the cluster-specific regulators, this process is implemented through R language "calcRSS"

function and visualized through ggplot2.

Cell-cell communication analysis.

To compare the changes of the cell-cell interactions among ES, TS and XEN between the co-
culture and separate culture conditions, we performed cell-cell communication analysis using the
CellChat package(Jin *et al.*, 2021). Following the official workflow, we calculated the potential
ligand-receptor interactions among the three cell lineages in each condition and then compared
the numbers and strength of these interactions between the two conditions. Briefly, loaded the
normalized counts into CellChat and applied the standard preprocessing steps, including the
functions "identifyOverExpressedGenes", "identifyOverExpressedInteractions", and
"projectData" with a standard parameter set. We then calculated the potential ligand-receptor
interactions between infected and non-infected cells based on the functions
"computeCommunProb", "computeCommunProbPathway", and "aggregateNet" using standard
parameters, all of the above procedures use default parameters.

CRISPR knockout.

We used the online software Benchling CRISPR to design all single guide RNAs (sgRNAs) used
in this study. The sequences of sgRNAs are included in Table S7. sgRNAs were cloned into the
pSpCas9(BB)-2A-eGFP (Addgene, PX458) plasmid by ligating annealed oligonucleotides with
BbsI-digested vector. The plasmid carrying the specific sgRNA was then transfected into FTW-
mESCs or FTW-mXENs by using an electroporator (NEPA2, Nepa Gene 1). EGFP positive cells
were sorted by flow cytometry after 48 h transfection and 2000 cells were plated in one well of a
6 well plate. Single clones were picked and expanded. Homozygous knockout clones were
confirmed by Sanger sequencing.

Plasmids.

pSpCas9(BB)-2A-eGFP (PX458) plasmid was purchased from Addgene (plasmid 48138).
pCAG-IP-mKO, pCAG-IP-eGFP plasmids were obtained from T. Hishida.

Statistical Analysis.

All quantitative data is presented as the mean ± SD. Experiments were repeated at least three
times (repeat number was indicated as "n" in figure legends). Differences between groups were
evaluated by Student's t-test (two-sided). *P* values are shown in the figures. Graphic analyses
were done using GraphPad Prism version 7.0 and 8.0 (GraphPad Software, La Jolla, Ca) and
Microsoft Excel (Microsoft 365).

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Figure. 1

A Mouse (m) Blastocyst → FGF ON / TGFβ ON / Wnt ON → FTW-mXENs / FTW-mTSCs / FTW-mESCs

B Mouse (m): FTW-mXENs, FTW-mTSCs, FTW-mESCs

C FTW-mXENs: GATA6, SOX17; FTW-mTSCs: CDX2, EOMES; FTW-mESCs: SOX2, OCT4

D E11.5 — Embryo, Yolk sac, Placenta

E GFP / GATA6 / GATA4 / DAPI

F Embryo, Placenta, E11.5

G GFP / CK8 / DAPI — Decidua layer, Giant cell layer, Spongiotrophoblast layer, Labyrinth layer

Figure. 2

Figure. 3

Figure. 4

Figure. 5

Figure. 6

A

B

C

Signaling pathways regulating pluripotency of stem cells; VEGF signaling pathway
NANOG, POU5F1, SOX2, PRDM14, CDX2, PRDM11, KLF7, COL9A1, RAC2, PRKCB, KDR

ECM-receptor interaction; TGF-beta signaling pathway
PDGFRA, NID2, LAM1, ID2, SOX17, GATA4, CDH2, ITGA6, LAMB4, TNC, BMP2, ACVR1C

ECM-receptor interaction; Hippo signaling pathway
GATA2, GATA3, KRT7, KRT8, KRT18, S100A11, CDH1, TFAP2C, LAMA3, ITGA1, BMP2, NKD1

D

(Niu et al, Science 2019; Ma et al, Science 2019; Nakamura et al, Nature 2016)

Figure. 7

A

cyESCs only

cyESCs + cyTSCs

cyESCs + cyXENs

cyESCs + cyTSCs + cyXENs

cyESCs + Fibroblast

Day 1 Day 2 Day 3 Day 4 Day 5

FTW-cyESCs   ▲ FTW-cyTSCs   ▲ FTW-cyXENs

B

C

D

Figure S1

Figure S1. Derivation, characterization of FTW-mXENs, FTW-mTSCs and FTW-mESCs and developmental potential of FTW-mXENs and FTW-mTSCs.

(A) Representative BF images of an E4.5 mouse blastocyst (upper left), day 8 outgrowth (bottom left) and passage 1 (right) during FTW stem cells derivation. Higher magnification images of the boxed areas are shown in the middle panel. Scale bars, 100 μm.

(B) Flow cytometry results showing the expression of GATA6 and EOMES in FTW-mXENs (left) and FTW-mTSCs (right).

(C) qRT-PCR results showing the relative expression levels of lineage markers in FTW-mESCs, FTW-mXENs and FTW-mTSCs. (mean ± SD, n = 3, biological replicates).

(D) Representative IF images of PDGFRa and SOX17 of FTW-mXENs. Scale bar, 100 μm.

(E) A representative IF image of TFAP2c of FTW-mTSCs. Scale bar, 100 μm. (F) to (I), Representative BF (F and H) and IF images (G and I) of conventional mXENs

(F and G) and mTSCs (H and I). Scale bars, 100 μm. (J) RT-PCR results showing the expression of lineage markers in conventional mXENs and mTSCs and converted FTW-mXENs and FTW-mTSCs. GAPDH, loading control.

(K) Doubling time of conventional mXENs (n = 5, biological replicates), mTSCs (n = 5, biological replicates), converted FTW-mXENs (n = 8, biological replicates), and converted FTW-mTSCs (n = 5, biological replicates). Box-and-whisker plots showing the median value (bar inside box), 25th and 75th percentiles (bottom and top of box, respectively), and minimum and maximum values (bottom and top whisker, respectively).

(L) qRT-PCR results showing the relative expression levels of several PE and VE markers in randomly differentiated FTW-mXENs at indicated timepoints (mean ± SD, n = 3, biological replicates).

(M) Representative images showing the appearance and H&E staining of a XEN-teratoma. A higher magnification image of the boxed area is shown on the right.

(N) Representative IF images of AFP, GATA6, PAX6 and T in XEN-teratoma sections. Blue, DAPI. Scale bars, 100 μm.

(O) A representative IF image of FOXA1 and COL6A1in a XEN-teratoma section.

(P) Representative BF and DAPI staining image of randomly differentiated FTW-mTSCs at day 12. Yellow dashed lines indicate multinucleated cells. Scale bar, 100 μm.

(Q) Representative images showing the appearance and H&E staining of a TSC-teratoma. A higher magnification image of the boxed area is shown in the right panel.

(R) qRT-PCR results showing the relative expression levels of trophoblast differentiation-associated genes in random differentiated FTW-mTSCs at indicated timepoints (mean ± SD, n = 3, biological replicates).

(S) Representative BF and fluorescence images showing chimeric contribution of mKO-labeled FTW-mXENs (left) and FTW-mTSCs (right) to E11.5 mouse conceptuses. Scale bars, 1 mm.

Figure. S2

Figure S2. Transcriptomic analyses of mouse FTW stem cells.

(A) Correlation analysis of FTW-mXENs, FTW-mTSCs, FTW-mESCs and published datasets of mPSCs(Bao et al., 2018; Cruz-Molina et al., 2017; Wu et al., 2015; Ye et al., 2018; Zhao et al., 2015), mTSCs(Cui et al., 2019; Kubaczka et al., 2015; Wu et al., 2011) and mXENs(Anderson et al., 2017; Zhong et al., 2018).

(B) The expression levels (log2 [FPKM\10+1]) of epiblast, trophoblast and extraembryonic endoderm markers in FTW-mESCs, FTW-mTSCs, and FTW-mXENs obtained from RNA-seq datasets.

(C) Correlation analysis of FTW-mXENs, FTW-mTSCs, FTW-mESCs and published datasets from mouse embryos and stem cell embryo models.

(D) PCA plots of RNA-seq datasets from FTW-mESCs, FTW-mTSCs, and FTW-mXENs and in vivo E3.5-E6.5 mouse conceptuses. Inner cell mass (ICM), Epiblast (Epi), Primitive endoderm (PrE), Visceral endoderm (VE), Extraembryonic endoderm (ExE).

(E) UMAP analysis of scRNA-seq datasets of FTW-mESCs, FTW-mTSCs, FTW-mXENs and in vivo E5.5 mouse conceptuses (EPI, PrE and TE cells).

Figure. S3

Figure S3. Proliferation restriction of FTW-mESCs by FTW-mXENs.

(A) Bar plot showing the cell densities of FTW-mESCs in day 5 separate and different co-cultures.

(B) Bar plot showing the cell densities of FTW-mESCs in separate and co-cultures (different mESCs: mTSCs and/or mESCs:mXENs ratios)

(C) Representative BF and fluorescence merged images of day 5 3D separate and co-cultures (different mESCs:mXENs ratios). Green, FTW-mESCs. Scale bar, 100 μm.

(D) Bar plot showing the total cell number of day 5 3D separate and co-cultures (different mESCs:mXENs ratios) (mean ± SD, n = 2, biological replicates).

(E) Representative IF images showing the expression of Activated Caspase 3 in separately cultured FTW-mESCs (bottom) and FTW-mESCs co-cultured with FTW-mXENs (top). Scale bars, 100 μm.

(F) Bar plot showing the percentages of Caspase3+ cells in separately cultured FTW-mESCs (left) and FTW-ESCs co-cultured with FTW-mXENs (right). (mean ± SD, n = 3, biological replicates, N.S., not significant).

(G) Representative IF images showing the expression of GATA6 and SOX2 in co-cultured FTW-mXENs (mKO) and FTW-mESCs (GFP), respectively. Scale bars, 100 μm.

(H) Bar plot showing the cell densities of FTW-mESCs in day 5 separate, contact and non-contact (transwell) co-cultures (mean ± SD, n = 3, biological replicates).

(I) Representative BF and fluorescence merged images of FTW-mESCs and FTW-mXENs in micropatterned co-cultures from day 1 to day 4. Scale bars, 100 μm. Yellow arrowhead, a standalone FTW-mESCs colony. Red arrowheads, FTW-mESCs colonies adjacent to FTW-mXENs.

(J) Representative H&E staining images of a teratoma generated from FTW-mESCs alone (top) and FTW-mESCs co-injected with FTW-mXENs (bottom).

(K) Weight of teratoma formed by FTW-mESCs and FTW-mESCs co-injected with FTW-mXENs at different mix ratios (mean ± SD, n = 3, biological replicates). (L) Bar plot showing the area of each in vitro cultured E6.5-6.75 mouse epiblast with (red) or without (green) VE (mean ± SD, n = 10, biological replicates). *P-value < 0.01, **P-value < 0.001. P-values were calculated using two-tailed Student's t test.

Figure. S4

Figure S4. Mechanistic insights of growth inhibition and transcriptomic analyses of co-cultured FTW stem cells.

(A) Joint UMAP embedding of single-cell transcriptomes from separately- and co-cultured FTW-mESCs, FTW-mXENs or FTW-mTSCs.

(B) Percentage of cells in each cluster derived from separately and co-cultured FTW-mESCs, FTW-mXENs or FTW-mTSCs.

(C) Representative BF and fluorescence merged images of separately- and co-cultured FTW-mESCs, as well as separately cultured FTW-mESCs supplemented with different ECM proteins. Scale bar, 100 μm.

(D) Bar plot showing the cell densities of FTW-mESCs in day 5 separate and co-cultures, as well as separate cultures supplemented with different ECM proteins (mean ± SD, n = 3, biological replicates, N.S., not significant).

(E) Representative BF and fluorescence merged images of separately- and co-cultured FTW-mESCs (with WT or *Lamc*-/- FTW-mXENs [clones #4 and #6]).

(F) Bar plot showing the cell densities of FTW-mESCs in day 5 separate and co-cultures (with WT of *Laminin*-/- FTW-mXENs) (mean ± SD, n = 3, biological replicates).

(G) Representative BF and fluorescence merged images of separately and co-cultured FTW-mESCs (WT or *Itgb1*-/- [clones #2 and #6]) Scale bar, 100 μm.

(H) Bar plot showing the relative cell densities of FTW-mESCs (WT or *Integrin-β1*-/-) in day 5 separate and co-cultures (mean ± SD, n = 3, biological replicates).

(I) A VENN diagram showing shared 502 DEGs (492 down-regulated; 10 up-regulated) between separately cultured FTW-mESCs and FTW-mESCs co-cultured with FTW-mXENs or with both FTW-mXENs and FTW-mTSCs.

(J) A heatmap showing the expression levels of AP-1 family members in separately (FTW-mESCs) and co-cultured (FTW-mESCs-co) FTW-mESCs.

(K) and (L), Enriched GO terms (K) and Bioplanet terms (L) for 492 down-regulated genes from (I).

(M) MMP expression levels (FPKM value) in separately cultured FTW-mESCs, FTW-mESCs co-cultured with FTW-mXEN (top), and FTW-mESCs co-cultured with FTW-mXENs and FTW-mTSCs (bottom).

Figure. S5

Figure S5. Derivation and characterization of FTW-cyXENs, FTW-cyTSCs and FTW-cyESCs.

(A) Growth curve of FTW-cyXENs (passage 26) (n =9, biological replicates).

(B) Karyotype analysis of FTW-cyXENs.

(C) RT-PCR results showing the expression of several hypoblast markers in FTW-cyXENs. M, DNA ladder. N.C., non-template control.

(D) Representative IF images showing GATA4, SOX17, FOXA2, GATA3 and OCT4 expression patterns in FTW-cyXENs. Blue, DAPI. Scale bars, 50 μm.

(E) Growth curve analysis of FTW-cyTSCs (passage 16) (n = 2, biological replicates).

(F) Karyotype analysis of FTW-cyTSCs.

(G) RT-PCR results showing the expression of several trophoblast markers in FTW-cyTSCs. M, DNA ladder. N.C., non-template control.

(H) Representative IF images showing TFAP2C expression in FTW-cyTSCs. Blue, DAPI. Scale bar, 50 μm.

(I) RT-PCR results showing the expression of VE/YE and EXMC related genes in differentiated FTW-cyXENs at day 9.

(J) Representative BF and H&E staining images of a TSC-teratoma generated from FTW-cyTSCs at day 7 post-injection.

(K) Representative IF images showing the expression patterns of EVT (HLAG), SCT (HCG), and TSC (GATA3 and TFAP2C) marker genes in FTW-cyTSCs derived TSC-teratoma sections. Blue, DAPI. Scale bars, 50 μm.

(L) Growth curve of FTW-cyESCs (passage 9) (n = 3, biological replicates).

(M) Representative IF images showing the expression of OCT4 and SOX2 in FTW-cyESCs. Blue, DAPI. Scale bars, 50 μm.

Figure. S6

Figure S6. Lineage crosstalk among co-cultured cynomolgus monkey FTW stem cells.

(A) Growth curves of separately and co-cultured (with FTW-cyXENs) tFTW-cyESCs (n=3, biological replicates).

(B) to (D), DEGs of separately cultured and co-cultured FTW-cyESCs (B), FTW-cyXENs (C), and FTW-cyTSCs (D). Top enriched GO terms were shown on the right.

(E) Heatmaps showing top 10 outgoing (left) and incoming (right) signaling in co-culture of FTW-cyESCs and FTW-cyXENs.

(F) Representative BF and fluorescence merged images of separately- and co-cultured FTW-cyESCs, as well as separately cultured FTW-cyESCs supplemented with different ECM proteins. Scale bar, 100 μm.

(G) Bar plot showing the cell densities of FTW-cyESCs in day 5 separate and co-cultures, as well as separate cultures supplemented with different ECM proteins (n=3, biological replicates).

Figure. S7

Figure S7. Cross-species comparison.

(A) to (C) SCENIC analysis showing divergent (left) and conserved (middle) TF-driven regulons in each mouse and monkey stem cell. Right, VENN plots showing common and distinct targets (between mice and cynomolgus monkeys) of well-known lineage TFs including NANOG, SOX17 and GATA3. See Table S6 for the all the target lists. Red dots represent the gene regulatory networks regulated by corresponding transcription factor related to the RBPS.

(D) Cross-species comparison of signaling crosstalk among embryonic and extraembryonic cells.