Generation of kidney tubular organoids from human pluripotent stem cells

Citation
Yamaguchi, S., R. Morizane, K. Homma, T. Monkawa, S. Suzuki, S. Fujii, M. Koda, et al. 2016. “Generation of kidney tubular organoids from human pluripotent stem cells.” Scientific Reports 6 (1): 38353. doi:10.1038/srep38353. http://dx.doi.org/10.1038/srep38353.

Published Version
doi:10.1038/srep38353

Permanent link
http://nrs.harvard.edu/urn-3:HUL.InstRepos:29738960

Terms of Use
This article was downloaded from Harvard University’s DASH repository, and is made available under the terms and conditions applicable to Other Posted Material, as set forth at http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#LAA

Share Your Story
The Harvard community has made this article openly available. Please share how this access benefits you. Submit a story.

Accessibility
Generation of kidney tubular organoids from human pluripotent stem cells

Shintaro Yamaguchi1, Ryuji Morizane1,2,3,4, Koichiro Homma1,5, Toshiaki Monkawa1,6, Sayuri Suzuki5, Shizuka Fujii5, Muneaki Koda1, Ken Hiratsuka1, Maho Yamashita7, Tadashi Yoshida7, Shu Wakino1, Koichi Hayashi1, Junichi Sasaki1, Shingo Hori5 & Hiroshi Itoh1

Recent advances in stem cell research have resulted in methods to generate kidney organoids from human pluripotent stem cells (hPSCs), which contain cells of multiple lineages including nephron epithelial cells. Methods to purify specific types of cells from differentiated hPSCs, however, have not been established well. For bioengineering, cell transplantation, and disease modeling, it would be useful to establish those methods to obtain pure populations of specific types of kidney cells. Here, we report a simple two-step differentiation protocol to generate kidney tubular organoids from hPSCs with direct purification of KSP (kidney specific protein)-positive cells using anti-KSP antibody. We first differentiated hPSCs into mesoderm cells using a glycogen synthase kinase-3β inhibitor for 3 days, then cultured cells in renal epithelial growth medium to induce KSP+ cells. We purified KSP+ cells using flow cytometry with anti-KSP antibody, which exhibited characteristics of all segments of kidney tubular cells and cultured KSP+ cells in 3D Matrigel, which formed tubular organoids in vitro. The formation of tubular organoids by KSP+ cells induced the acquisition of functional kidney tubules. KSP+ cells also allowed for the generation of chimeric kidney cultures in which human cells self-assembled into 3D tubular structures in combination with mouse embryonic kidney cells.

Accumulating evidence revealed critical roles of kidney tubular cells in kidney fibrosis, the most important pathological process which leads to the progress of chronic kidney disease (CKD)1-8. To facilitate studies on human kidney fibrosis and CKD, it is needed to establish new tools of human kidney tubular cells in vitro, since current immortalized human tubular cell lines and primary culture of human proximal tubular cells have limitations due to dedifferentiated phenotypes. Human pluripotent stem cells (hPSCs), by virtue of their unlimited self-renewal and ability to generate cells of all three germ layers of the embryo, are attractive sources for disease modeling as well as regenerative medicine. Significant advances have been made within the past decade that led to generation of kidney lineage cells from mouse and human PSCs9-23. Recent studies showed generation of kidney organoids from hPSCs, which contained multiple cell types with characteristics of podocytes, proximal tubules, loops of Henle, and distal tubules21,23. However, the methods to induce specific cell types of kidneys from hPSCs have not been well-established, which would facilitate studies on kidney bioengineering, cell transplantation, and disease modeling.

Sharmin et al. recently demonstrated a method to purify NPHS1-expressing cells from differentiated human induced pluripotent stem cells (hiPSCs), which formed vascularized glomeruli when transplanted into kidney capsules of mice24. They generated hiPSCs that express green fluorescent protein (GFP) in the NPHS1 locus. NPHS1 was identified as a causative gene for Finnish-type congenital nephrotic syndrome, and is exclusively expressed in podocytes in vivo25. Hence, NPHS1-expressing cells are very likely to have characteristics of podocytes, justifying their approach to isolate NPHS1-expressing cells from differentiated hPSCs in order to obtain pure population of podocytes.

1Department of Internal Medicine, Keio University School of Medicine, 35 Shinnomachi, Shinjuku-ku, Tokyo 160-8582, Japan. 2Renal Division, Brigham and Women’s Hospital, 75 Francis Street, Boston, MA 02115, USA. 3Department of Medicine, Harvard Medical School, 25 Shattuck St, Boston, MA 02115, USA. 4Harvard Stem Cell Institute, 7 Divinity Ave, Cambridge, MA 02138, USA. 5Emergency and Critical Care Medicine, Keio University School of Medicine, 35 Shinnomachi, Shinjuku-ku, Tokyo 160-8582, Japan. 6Medical Education Center, Keio University School of Medicine, 35 Shinnomachi, Shinjuku-ku, Tokyo 160-8582, Japan. 7Apheresis and Dialysis Center, Keio University School of Medicine, 35 Shinnomachi, Shinjuku-ku, Tokyo 160-8582, Japan. Correspondence and requests for materials should be addressed to K.H. (email: homma@keio.jp)
To obtain pure population of kidney tubular cells, we focused on one of cadherins, Kidney-specific protein (KSP; cadherin 16) which is exclusively expressed in kidney lineage cells including ureteric buds, developing nephrons, mesonephric tubules, Bowman’s capsules, proximal tubules, loops of Henle, and distal and collecting tubules. We previously generated a monoclonal antibody against KSP which enabled us to purify KSP+ cells by flow cytometry. Building on these prior reports, the aim of this study was to establish a rapid and simple differentiation protocol of human embryonic stem cells (hESCs) into kidney tubular cells with purification of KSP+ cells and to generate tubular organoids in 3D culture systems. We employed a feeder-free monolayer culture system to differentiate hESCs into KSP+ cells, and established a simple two-step differentiation protocol using a glycogen synthase kinase-3β (GSK-3β) inhibitor (BIO: 6-bromoindirubin-3′-oxime) in order to obtain sufficient number of KSP+ cells for flow sorting. We also showed that these KSP+ cells derived from hESCs exhibited characteristics of all segments of kidney tubular cell and acquired more functional characteristics when they formed tubular organoids in 3D Matrigel. In addition, we demonstrated that the KSP+ cells form tubular structures in chimeric culture with dissociated mouse metanephric kidneys, supporting our hypothesis that purification of KSP+ cells from differentiated hPSCs provides pure population of kidney tubular cells.

**Results**

**Differentiation of hESCs into KSP+ cells.** We developed a simple two-step protocol to differentiate K-hESCs into KSP+ cells within 10 days. Given the fact that embryoid body (EB) formation might be a time-consuming differentiation process and also hinder the effective delivery of differentiation-inducing signals to all cells, we employed a two-dimensional feeder-free monolayer culture system. In vivo, the kidneys develop from the intermediate mesoderm (IM) which arises from the primitive streak. Hence, K-hESCs were first differentiated into the cells of the primitive streak with a GSK-3β inhibitor (BIO, a WNT activator) (BIOt+); BIO-treated cultures) for 3 days, or without BIO (mock; BIO-untreated cultures) as a negative control (Fig. 1a). Accordingly, the expression of the primitive streak marker BRACHURY was measured by real time quantitative reverse transcriptase polymerase chain reaction (qRT-PCR) was transiently increased, whereas the expression of the pluripotency marker OCT3/4 was down-regulated with BIO treatment (Fig. 1b). To determine whether additional growth factors to REGM further enhance KSP expression, we tested activin A (10 ng/ml), hepatocyte growth factor (HGF; 10 ng/ml) or insulin-like growth factor 1 (IGF-1; 10 ng/ml) from day 3 to day 10 of differentiation, since our previous study showed that HGF and IGF-1 increased KSP expression in mouse ESCs differentiated with DMEM supplemented with activin A 10 ng/ml. Any of activating A, HGF or IGF-1, however, did not further increase KSP expression compared to REGM alone on day 10 of differentiation (Fig. 1c), suggesting that REGM itself was optimized for differentiation of hESCs into kidney tubular cells. We also evaluated other lineage markers by qRT-PCR in hESCs on day 10 of differentiation; PAX6 (an endoderm/ectoderm marker) or NKX2-5 (a cardiac mesoderm marker) (Fig. 1d). Those two genes were not upregulated by our differentiation protocol with BIO and REGM while nephron progenitor markers including OSR1, WT1, GDNF, CITED1, HOXD11 (Fig. 1d and Fig. S1) and kidney tubular markers including KSP, GTF, AQP1, CD13, AQP1B, MEGALIN, SGLT1, UROMODULIN, AQP 2 were significantly upregulated (Fig. 1e), suggesting that hESCs were differentiated into kidney lineage cells with the two-step differentiation protocol.

Collectively, these qRT-PCR results indicated that the first specification into the primitive streak cells with BIO for 3 days subsequently induced the intermediate mesoderm cells and kidney lineage cells which represent a heterogeneous population containing cells with characteristics of intermediate mesoderm, metanephric mesenchyme, developing nephron, and glomerular podocytes (WT1) and tubular cells (KSP) with stochastic differentiation within 10 days of the differentiation beginning.

**Purification of KSP+ cells from differentiated hESCs.** To obtain pure population of kidney tubular cells from differentiated hESCs with our two-step protocol, we used anti-KSP antibody for flow sorting, which was designed to recognize the extracellular domain of KSP. To evaluate the specificity and cross-reactivity of anti-KSP antibody to human kidney tubular cells, we performed a flow cytometric analysis and immunocytochemistry using a human embryonic kidney (HEK) 293 cell line as a positive control and human aortic smooth muscle cells (HASMCs) as a negative control as indicated by qRT-PCR and western blotting (Fig. 2a,b). Western blotting with anti-KSP antibody detected several bands (Fig. 2b, left). However, a band of 75–100 kDa was not reacted with the secondary antibody alone, suggesting that this band is specific for KSP (Fig. 2b, right). The flow cytometric analysis detected KSP+ cells in HEK293 cells but not in human aortic smooth muscle cells (HASMCs) (Fig. 2c). Immunocytochemistry showed a positive staining on the cell surface of HEK293, which is consistent with protein localization of KSP in kidneys in vivo (Fig. 2d). In addition, we performed immunohistochemistry of human kidney samples using the anti-KSP antibody, anti-AQP1 antibody, and anti-AQP2 antibody (Fig. 2e–g). KSP+ cells were co-localized with AQP1+ cells which represent proximal tubules (Fig. 2f), AQP2+ cells which represent collecting ducts (Fig. 2g), which is in accordance with the results previously obtained in mouse neonatal kidney tissues and human kidney. These data demonstrated that our original anti-KSP antibody detected human KSP as well as mouse KSP.
To obtain KSP+ cells from stochastically differentiated hESCs, we evaluated the protein expression of KSP in differentiated hESCs using the anti-KSP antibody. Immunohistochemistry showed that KSP was expressed on the surface of cells in a small population of differentiated hESCs along the periphery of cell clusters on day 10 of the differentiation with BIO and REGM (Fig. 3b,c), whereas KSP staining was not detected in hESCs in BIO-untreated (mock) cells (Fig. 3a), which was consistent with the results obtained by qRT-PCR (Fig. 1b). Western blotting also detected positive bands in samples treated with BIO, but not in samples treated with mock in 2 independent experiments (Fig. 3d).

To exclude the possibility of nonspecific labelling of the anti-KSP antibody, we performed flow cytometry using anti-TRA1-60 (tumour rejection antigen 1-60) antibody in combination with the anti-KSP antibody. Immunohistochemistry showed that KSP was expressed on the surface of cells in a small population of differentiated hESCs along the periphery of cell clusters on day 10 of the differentiation with BIO and REGM (Fig. 3b,c), whereas KSP staining was not detected in hESCs in BIO-untreated (mock) cells (Fig. 3a), which was consistent with the results obtained by qRT-PCR (Fig. 1b). Western blotting also detected positive bands in samples treated with BIO, but not in samples treated with mock in 2 independent experiments (Fig. 3d).

To exclude the possibility of nonspecific labelling of the anti-KSP antibody, we performed flow cytometry using anti-TRA1-60 (tumour rejection antigen 1-60) antibody in combination with the anti-KSP antibody. Immunohistochemistry showed that KSP was expressed on the surface of cells in a small population of differentiated hESCs along the periphery of cell clusters on day 10 of the differentiation with BIO and REGM (Fig. 3b,c), whereas KSP staining was not detected in hESCs in BIO-untreated (mock) cells (Fig. 3a), which was consistent with the results obtained by qRT-PCR (Fig. 1b). Western blotting also detected positive bands in samples treated with BIO, but not in samples treated with mock.
Characterization of KSP+ cells. We confirmed the presence of sufficient KSP+ cells in hESCs by flow cytometry on day 10 of the differentiation with our two-step protocol (Fig. 3f). To characterize KSP+ cells purified from differentiated hESCs with our two-step differentiation protocol (Fig. 4a), we purified KSP+ cells from differentiated hESCs with flow cytometry using the KSP-antibody on day 10 of the differentiation and evaluated gene expression of kidney tubular markers by qRT-PCR. Gene expression in KSP+ cells were compared to that in whole differentiated hESCs on day 10 of the differentiation (BIO+, unsorted, Fig. 4b), which were not subjected to flow sorting, in order to evaluate how efficiently flow sorting with the KSP-antibody improved purity of kidney tubular cells. KSP+ cells purified by flow sorting showed significantly higher expression of KSP than unsorted hESCs by qRT-PCR (Fig. 4b), demonstrating that flow sorting with the KSP-antibody significantly improved purity of KSP+ tubular cells. qRT-PCR also showed that MEGALIN, AQP1, UROMODULIN and AQP2 were higher in KSP+ cells than in unsorted hESCs (Fig. 4b).

In order to further characterize purified KSP+ cells, we compared gene expressions of kidney tubular markers in KSP+ cells to those in primary renal proximal tubular epithelial cells (RPTECs). KSP+ cells showed a comparable expression of AQP1 as RPTECs, whereas the expressions of UROMODULIN, SLC12A3 and AQP2 were higher in KSP+ cells than RPTECs (Fig. 4c). These data suggest that KSP+ cells have characteristics of proximal tubular, loops of Henle, distal tubular and collecting duct cells.18-21
We then evaluated the functional characteristics of purified KSP+ cells by mRNA expression and activity of γ-glutamyl transferase (GGT), which is known to be expressed in the proximal tubule15,43. The modest increase of GGT in purified KSP+ cells compared with unsorted hESCs on day 10 of differentiation (1.45 ± 0.25-fold) is most likely due to the fact that the basal level of GGT mRNA level in unsorted hESCs are already high (Fig. 4b), since GGT is expressed in various tissues43. In order to analyse the GGT activity, which reflects the functional characteristic of proximal tubular cells15, we measured p-nitroaniline which is released by the action of GGT 15. KSP+ cells as well as RPTECs demonstrated GGT activity (Fig. 4e); however, the GGT activity in the RPTECs was about six times as high as that in KSP+ cells, consistent with the relative gene expression level of GGT in KSP+ cells and RPTECs (Fig. 4d). These results suggest that KSP+ cells are a heterogeneous population containing not only proximal tubules but also other segment cells, though another possible explanation is that KSP+ cells are functionally less mature than RPTECs. In addition, as our previous study showed that tubular formation in Matrigel with Wnt4 further promoted differentiation of KSP+ cells derived from mESCs into more functional proximal tubules and collecting duct cells13, we hypothesized that same approaches would further facilitate functional maturation of KSP+ cells derived from hESCs. First, we investigated the capacity of KSP+ cells for tubular organoids formation in vitro by transferring onto Matrigel (Fig. 4f). KSP+ cells formed small and sparse tubular structures in Matrigel alone (Fig. 4g). Cross-section slides of those tubular structures showed cilia-like structures at the luminal surface (Fig. 4h). Consistent with this, staining of the ciliary marker, acetylated TUBULIN was observed18, indicating that kidney tubular organoids generated from purified KSP+ cells have cellular polarity.
(Fig. 4i). Furthermore, we tested a co-culture with NIH3T3-Wnt4 cells that constitutively express Wnt4, which is essential for tubulogenesis\(^{13,44}\). After 24 h of culture, the KSP+ cells formed abundant tubular organoids that co-expressed MEGALIN, AQP1 or AQP2 (Fig. 4j–m), demonstrating that KSP+ cells have characteristics of kidney tubular cells. In contrast, KSP negative cells just formed petal-like structures that were negative for KSP and MEGALIN (Fig. S2). Accordingly, the gene expression of KSP, AQP1, and AQP2 was increased upon Wnt4 stimulation after 48 h of co-culture (Fig. 4n), suggesting the induction and maturation of proximal tubules and collecting ducts. These findings indicate that KSP+ cells possess the functional characteristics of kidney tubular cells and formed tubular organoids in 3D Matrigel.

**Formation of tubular structures in chimeric culture with dissociated mouse metanephric kidneys.** To confirm our results that KSP+ cells have characteristics of kidney tubular cells, we examined functional integration of KSP+ cells into 3D renal structures during the re-aggregation of embryonic mouse metanephric cells, as described previously\(^{14,17,27,45}\). In this assay, dissociated cells from wild-type E11.5 mouse
embryonic kidneys, which can recapitulate nephrogenesis were re-aggregated with KSP+ cells purified from differentiated hESCs on day 10 of the differentiation (Fig. 5a). Since a previous study demonstrated that undifferentiated hPSCs disrupted the formation of 3D structures by murine cells, we excluded undifferentiated hESCs with anti-TRA1-60 antibody. After 7 days of chimeric culture in REGM, we performed immunohistochemistry for human mitochondria in order to identify hESC-derived cells (Fig. 5b,c). Human mitochondria positive cells formed 3D tubular structures positive for the proximal tubule marker, lotus tetragonolobus lectin (LTL) (Fig. 5b,c) in combination with mouse embryonic kidney cells. These data demonstrate that KSP+ cells are committed to kidney tubular cells.

Discussion
We demonstrated a rapid and simple differentiation protocol of hESCs into kidney tubular cells, direct purification of kidney tubular like cells with the anti-KSP antibody and generation of tubular organoids in 3D culture systems. We have previously shown that mESC-derived KSP+ cells exhibit characteristics of kidney tubular phenotypes and have suggested that KSP can serve as a kidney lineage marker during mESC differentiation. Here, we successfully generated the KSP+ cell population from hESCs with stochastic differentiation after induction of primitive streak in approximately half the time compared to that required for the differentiation of mouse ES cells. In addition, KSP+ cells derived from hESCs exhibited the functional characteristics of kidney tubular cells, formation of tubular organoids in 3D Matrigel, and the generation of chimeric kidney cultures.

In the present study, the differentiation of hESCs was achieved by a monolayer culture method that did not require feeders, high serum concentration, or EB formation. Previous studies have reported that the signalling induced by extracellular matrix components plays an important role in directing early kidney differentiation, suggesting that this process might be promoted in a monolayer culture. On the other hand, EB formation and feeder cell contamination might hinder the initiation of such signalling and certain growth factors present in serum have been shown to antagonize hESC differentiation.

The inhibition of GSK-3β, which is a serine/threonine kinase, leads to the activation of canonical Wnt/β-catenin signalling in ESCs, resulting in mesodermal differentiation. Therefore, during the first step of our protocol, KhES-1 cells were first differentiated into the cells of primitive streak cells with a GSK-3β inhibitor (BIO). As shown in this study, treatment of BIO induced BRACHYURY expression (Fig. 1b), indicating the induction of the primitive streak cells. Notably, previous studies suggested that the Brachyury-positive primitive
streak population is capable of differentiating into the Osr1-positive IM cells, the origin of kidney lineage\textsuperscript{16,28}. The induction of primitive streak cells from hPSCs is triggered by the activation of Wnt/β-catenin signalling, and subsequent differentiation into IM cells requires downregulation of Wnt activity\textsuperscript{16,49}. Therefore, in the second step of our protocol, we removed the Wnt/β-catenin stimulation and provided culture conditions suitable for the efficient generation of IM cells and kidney tubular cells\textsuperscript{15,31,32}. In our step-wise procedure, the treatment of KhES-1 cells with BIO for 3 d induced Brachyury expression resulting in a decrease of TRA1-60+ cells (Figs 1b and 3e), and subsequent culture in REGM induced the differentiation into KSP+ cells (Figs 1b and 3f). In contrast, BIO-untreated cultures did not induce KSP+/TRA1-60-negative cells on day 10 of differentiation (Fig. 3f). These results demonstrated that application of the GSK-3β inhibitor in conjunction with culture in REGM can efficiently promote the differentiation of hESCs into KSP+ kidney tubular cells.

Under these differentiation conditions, the gene expression of not only KSP but also WT1, which is known to be expressed in intermediate mesoderm, metanephric mesenchyme, developing nephron, and glomerular podocytes at the late stage of kidney differentiation\textsuperscript{44}, was upregulated on day 8–10 of differentiation. Given that the cell population after differentiation was heterogeneous, the KSP+/TRA1-60-negative cells were purified from differentiated hESCs using flow cytometry (Fig. 3f) to obtain pure population of kidney tubular cells.

Next, we evaluated the functional characteristics of purified KSP+ cells. GGT is expressed in the proximal tubule\textsuperscript{18,43} and produces p-nitroaniline. Thus, GGT activity reflects the functional characteristic of kidney tubular cells\textsuperscript{15}. Differentiated hESCs provides a population of definitive kidney tubular lineage cells.

To induce KhES-1 cell differentiation, cell clusters were transferred to type I collagen-coated dishes (Asahi Techno Glass Co., Ltd., Tokyo, Japan) and cultured for 1 day in DMEM/F12, 20% knockout serum replacement, 1% nonessential amino acids by volume, 2 mM L-glutamine, and 0.1 mM 2-mercaptoethanol supplemented with B27, N2 (Invitrogen), and 5μM GSK-3β inhibitor (BIO; Sigma-Aldrich) for 3 d. Under these differentiation conditions, we removed the inhibition of proximal tubules and collecting ducts with BIO-untreated cultures did not induce KSP+/TRA1-60-negative cells on day 10 of differentiation (Fig. 3f). In contrast, BIO-untreated cultures did not induce KSP+/TRA1-60-negative cells on day 10 of differentiation (Fig. 3f). These results demonstrated that application of the GSK-3β inhibitor in conjunction with culture in REGM can efficiently promote the differentiation of hESCs into KSP+ kidney tubular cells.

Conclusions

In this study, we have demonstrated a method to purify human kidney tubular cells from hESCs with the anti-KSP antibody after differentiation with a simple two-step differentiation protocol. This approach is useful for generating cells of definitive kidney tubular lineage cells that might be usable as a source for generation of bioengineered kidneys, modeling kidney diseases, drug screening for new therapeutic approaches for kidney diseases, nephrotoxicity assays, and ultimately kidney regenerative medicine using hPSCs.

Materials and Methods
Undifferentiated human ES cell culture. KhES-1 (46, XX) human ES cells (kindly provided by Kyoto University) were grown on mouse embryonic fibroblast (MEF) feeder layers (derived from embryonic day (E) 14.5 ICR mouse embryos and subsequently treated with mitomycin C (Sigma-Aldrich, St. Louis, MO, USA) and maintained at 37 °C and 5% CO₂. KhES-1 and MEFs were co-cultured in ES cell maintenance medium containing 77% Dulbecco's modified Eagle's medium (DMEM)/F12, 20% knockout serum replacement (Invitrogen), Carlsbad, CA, USA), 1% nonessential amino acids by volume (Invitrogen), 2 mM L-glutamine (Sigma-Aldrich), and 0.1 mM 2-mercaptoethanol (Gibco, Carlsbad, CA, USA), supplemented with 4 ng/ml recombinant human basic fibroblast growth factor (Wako Pure Chemical Industries, Ltd., Osaka, Japan). For routine passaging, every 5 or 6 days undifferentiated KhES-1 cells were detached with dissecting pipettes (Costar, Washington, DC, USA) and split at a ratio between 1:3 and 1:6.

Human ES cell differentiation. Undifferentiated KhES-1 cell colonies were detached with a solution containing 0.25% trypsin (Invitrogen), 20% knockout serum replacement (Invitrogen), 1 mg/ml collagenase (Wako) by volume, and 1 mM CaCl₂ (Wako) in phosphate-buffered saline (PBS) (Gibco), and dissociated into small cell clusters. Prior to differentiation, the cell clusters were filtered through a 40-μm nylon mesh cell strainer (BD Biosciences, San Jose, CA, USA) to remove MEFs.

To induce KhES-1 cell differentiation, cell clusters were transferred to type I collagen-coated dishes (Asahi Techno Glass Co., Ltd., Tokyo, Japan) and cultured for 1 day in DMEM/F12, 20% knockout serum replacement, 1% nonessential amino acids by volume, 2 mM L-glutamine, and 0.1 mM 2-mercaptoethanol, which was then replaced with DMEM/F12, 20% knockout serum replacement, 1% nonessential amino acids by volume, 2 mM L-glutamine, and 0.1 mM 2-mercaptoethanol supplemented with B27, N2 (Invitrogen), and 5μM GSK-3β inhibitor (BIO; Sigma-Aldrich) for 3 days (days 0–3). The medium was then changed to REGM supplemented with REGM SingleQuots (Lonza, Basel, Switzerland) containing 0.5% fetal bovine serum (PBS), and 0.1% recombinant human epidermal growth factor, insulin, hydrocortisone, epinephrine, triiodothyronine, transferrin, and gentamicin by volume. Cells were then incubated for an additional 7 days (days 3–10).

Flow cytometry. Cells were dissociated with trypsin/EDTA (Invitrogen) and treated with 0.2% collagenase type IV (Wako) for 15 min at 37 °C. The cells were mechanically dissociated by pipetting, then filtered through
a 70-μm cell strainer (Falcon, Corning, NY, USA) and maintained in DMEM containing 10% FBS for 1 h before treatment with 10μg/ml Fc blocker (#422301; Bio Legend, San Diego, CA, USA) for 20 min on ice. The cells were incubated with 0.08 mg/ml biotinylated anti-KSP antibody (originally produced by hybridomas) for 30 min, 0.01 mg/ml streptavidin-conjugated Alexa Fluor 647 (Invitrogen) for 20 min on ice, and finally with a fluorescein isothiocyanate (FITC)-conjugated monoclinal anti-TRA1–60 antibody (#560173; 1:200; BD Biosciences). Just prior to analysis, the cells were transferred to a 5 ml polypropylene tube (Falcon, Corning) to which 1μg/ml propidium iodide (Sigma–Aldrich) was added. Cells were counted and sorted using a flow cytometer (MoFlo XDP; Beckman Coulter, Brea, CA, USA) according to the manufacturer’s instructions. The KSP expression threshold was set relative to the signal intensity of negative control incubated without antibody or with the secondary antibody only.

### Tubular organoid formation in 3D Matrigel.

NIH3T3 cells that constitutively express Wnt4 (NIH3T3-Wnt4; kindly provided by Dr. Andy McMahon, University of Southern California, USA) were maintained in DMEM supplemented with 10% FBS. Cells were expanded in culture dishes after being mitotically inactivated by 10μg/ml mitomycin C for 2 h 45 min. Matrigel (BD Biosciences) was placed on inactivated NIH3T3-Wnt4. KSP-positive/TRA1–60 negative cells purified from KhES-1 cells were transferred onto Matrigel (BD Biosciences) in REGM and cultured for 24–48 h.

### RNA extraction, cDNA synthesis, PCR, and real-time PCR.

Total RNA was isolated using an miRNAasy Mini Kit (Qiagen, Valencia, CA, USA) and converted to cDNA using the High-Capacity Reverse Transcription Kit (Applied Biosystems, Carlsbad, CA, USA) according to the manufacturer’s instructions. Real-time PCR was performed using a QuantiFast SYBR Green PCR Kit (Qiagen) according to the manufacturer’s protocol. Expression levels were calculated using the 2−ΔΔCt method and normalized to levels of the internal control glyceraldehyde-3-phosphate dehydrogenase (GAPDH).

### Immunolabelling.

Human kidney tissue samples from two donors (OTB-2141; paraffin embedded kidney sections from a 62 years old, male; Capital Biosciences, Rockville, MD, USA, and HuFTS241; frozen kidney sections from a 54 years old, male; Biomax US Inc. Rockville, MD, USA) were immunolabelled as follows. Formalin-fixed paraffin embedded tissues were deparaffinised by two changes each of xylene and 100% ethanol, and then hydrated, followed by immersion in a target retrieval solution (Dako, Carpinteria, CA, USA). Frozen tissue sections were fixed in 4% paraformaldehyde (PFA) (Wako) in PBS for 15 min at room temperature. Both slides were blocked in PBS containing 4.0% bovine serum albumin (BSA) (Nichirei Biosciences, Inc., Tokyo, Japan) and 0.1% Triton X-100 (Wako), and incubated at 4°C overnight with one of the following primary antibodies diluted in 0.1% BSA/PBS: anti-KSP (1:100; originally produced by hybridomas), anti-AQP1 (#SC20810; 1:50; Santa Cruz Biotechnology, Inc., Dallas, TX, USA), or anti-AQP2 (#A7310; 1:200; Sigma–Aldrich). After washing with PBS/0.1% Tween 20 (Wako), the sections were incubated with Alexa Fluor 488- or 594-conjugated secondary antibodies (1:500; Invitrogen) for 1 h at room temperature. After counter-staining with DAPI (300 nM in PBS; Invitrogen) to visualize the nuclei, images were obtained using a LSM710 confocal microscope (Carl Zeiss Microscopy GmbH, Göttingen, Germany). KhES-1 cells on day 10, incubated with or without BIO (5μM) for the first 3 days of differentiation and HEK 293 cell line were stained after fixation with 4% PFA in PBS. Samples were blocked with PBS containing 4% BSA and incubated with anti-KSP antibody (1:100; originally produced by hybridomas), followed by an Alexa Fluor 488-conjugated secondary antibody (1:200; Invitrogen).

KSP-positive/TRA1–60 negative cells cultured in Matrigel with or without NIH3T3-Wnt4 cells and chimeric culture with dissociated mouse metanephric kidneys were blocked with PBS containing 4.0% BSA and 0.1% Triton X-100, then incubated with one of the following primary antibodies: anti-KSP (1:100; originally produced by hybridomas)13,18, anti-human-specific mitochondria (#ab3298; 1:50; Abcam), anti-AQP1 (#SC20810; 1:50; Santa Cruz Biotechnology), anti-AQP2 (#A7310; 1:200; Sigma–Aldrich), anti-Acetylated Tubulin (#T6793; 1:500; Sigma–Aldrich) or FITC-conjugated lotus tetragonolobus lectin (#FL-1321; LTL, 1:200; Vector Laboratories, Burlingame, CA, USA). After PBS washes, Alexa Fluor 488- or 594-conjugated antibodies (Invitrogen) and streptavidin-conjugated Alexa Fluor 647 (Invitrogen) were applied for signal detection.

### Western blot analysis.

Cells were washed twice with PBS and lysed in radioimmunoprecipitation buffer composed of 20 mM Tris-HCl (pH 7.4), 0.1% sodium dodecyl sulphate (SDS), 1% Triton X-100, and 1% Na deoxycholate (all from Wako). Protein lysates (20μg) were resolved by 10% Tris-glycine SDS polyacrylamide gel (Bio-Rad Laboratories, Inc., Hercules, CA, USA) electrophoresis using an Any kD precast gel (Bio Rad Laboratories) and transferred to Immobilon polyvinylidene fluoride membranes (Millipore, Marlborough, MA, USA), which were blocked with Tris-buffered saline containing 5% dried milk (Megmilk Snow Brand Co., Ltd., Hokkaido, Japan). Western-blotted protein extracts from KhES-1 cells were probed with antibodies against KSP (originally produced by hybridomas)13,18 or #ab116368; Abcam, Cambridge, MA) and β-actin (#A1978; Sigma–Aldrich) (loading control). Both slides were blocked in PBS containing 4% FBS and incubated with anti-KSP antibody (1:100; originally produced by hybridomas), followed by an Alexa Fluor 488-conjugated secondary antibody (1:200; Invitrogen).

### Chimeric kidney cultures.

Metanephric kidneys from imprinting control region (ICR) mice (Japan SLC, Inc., Shizuoka Prefecture, Japan) at embryonic day 11.5 were dissected in improved MEM (Invitrogen). Metanephric cells were dissociated in 0.05% trypsin/EDTA (Sigma–Aldrich) in PBS for 10 min at 37°C, stabilized in improved MEM containing 1% penicillin/streptomycin (Sigma–Aldrich) and 10% FBS for 10 min, then filtered through a 40-μm cell strainer. A total of 1 × 10^4 freshly dissociated metanephric cells and 1 × 10^4 KSP-positive/TRA1–60 negative cells derived from KhES-1 were mixed, seeded onto 96-well low-adhesion Lipidure-coated plates (NOF America Corp., White Plains, NY, USA) with REGM containing 10μM ROCK inhibitor Y-27632 (Sigma–Aldrich) and cultured
overnight to induce aggregate formation. The aggregates were then placed at the air-medium interface on polycarbonate filters (Millipore) with 0.4-μm pores for 1 week, with REGM replacement every 2 days. The resulting aggregates were fixed and serial sections were examined by immunostaining and imaged by confocal microscopy.

**γ-Glutamyltransferase (GGT) activity.** KSP-positive/TRA1-60 negative cells derived from KhES-1 and primary non-neoplastic human renal proximal tubular epithelial cells (RPTEC; Lonza, Cologne, Germany) (1 × 10^6) were homogenized in 200 μL ice-cold GGT Assay Buffer. γ-GGT activity colorimetric assay kit (MAK089; Sigma-Aldrich) was used according to the manufacturer’s protocol.

**Animal experiments.** All mice experiments were approved by the Institutional Animal Center at Keio University School of Medicine in accordance with the National Institutes of Health Guide for the Care and Use of Laboratory Animals.

**Statistical analysis.** The results are presented as the means ± S.E.M. Comparisons between groups were performed using a two-tailed Student’s t test. P < 0.05 was considered significant.

**References**

1. Yang, L., Besschetnova, T. Y., Brooks, C. R., Shah, J. V. & Bonventre, J. V. Epithelial cell cycle arrest in G2/M mediates kidney fibrosis after injury. *Nature medicine* **16**, 535–543, 531p following 143, doi: 10.1038/nm.2144 (2010).

2. Bielecki, B. et al. Epithelial Notch signaling regulates interstitial fibrosis development in the kidneys of mice and humans. *The Journal of clinical investigation* **120**, 4040–4054, doi: 10.1172/JCI43025 (2010).

3. Haegewa, K. et al. Renal tubular Sirt1 attenuates diabetic albuminuria by epigenetically suppressing Claudin-1 overexpression in podocytes. *Nature medicine* **19**, 1496–1504, doi: 10.1038/nm.3363 (2013).

4. Morizane, R. et al. mir-34c attenuates epithelial-mesenchymal transition and kidney fibrosis with ureteral obstruction. *Scientific reports* **4**, 4578, doi: 10.1038/srep04578 (2014).

5. Morizane, R. et al. mir-363 induces transdifferentiation of human kidney tubular cells to mesenchymal phenotype. *Clinical and experimental nephrology*, doi: 10.1007/s10157-015-1167-2 (2015).

6. Maarouf, O. H. et al. Paracrine Wnt1 Drives Interstitial Fibrosis without Inflammation by Tubulointerstitial Cross-Talk. *Journal of the American Society of Nephrology: JASN* **16**, 3527–3534, doi: 10.1681/ASN.2005050544 (2005).

7. Grande, M. T. et al. Positionally cloned gene for a novel glomerular protein–nephrin–is mutated in congenital nephrotic syndrome. *Nature* **395**, 707–711, doi: 10.1038/30736 (1998).

8. Kestila, M. et al. Positionally cloned gene for a novel glomerular protein–nephrin–is mutated in congenital nephrotic syndrome. *Molecular cell* **1**, 575–582 (1998).

9. Shao, X., Johnson, J. E., Richardson, J. A., Hiesberger, T. & Igarashi, P. A minimal Ksp-cadherin promoter linked to a green fluorescent protein reporter gene exhibits tissue-specific expression in the developing kidney and genitourinary tract. *J Am Soc Nephrol* **13**, 1824–1836 (2002).

10. Xia, Y. et al. Directed differentiation of human pluripotent cells to ureteric bud kidney progenitor-like cells. *Nat Cell Biol* **15**, 1507–1515, doi: 10.1038/ncb2872 (2013).

11. Rumballe, B. A. et al. Nephron formation adopts a novel spatial topology at cessation of nephrogenesis. *Developmental biology* **360**, 110–122 (2011).

12. Sonooyama, T. et al. Differentiation of human embryonic stem cells and human induced pluripotent stem cells into steroid-producing cells. *Endocrinology* **153**, 4336–4345, doi: 10.1210/en.2012-1060 (2012).

13. Tam, P. P. & Loebel, D. A. Gene function in mouse embryogenesis: get set for gastrulation. *Nat Rev Genet* **8**, 368–381, doi: 10.1038/nrg2084 (2007).
Supplementary information accompanies this paper at http://www.nature.com/srep
Additional Information

Acknowledgements
This research was supported by Grants-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology (KAKENHI, 23890203, 25461231, 26806043) and Daiwa Securities Health Foundation. We thank Sadafumi Suzuki and Yumi Matsuzaki at the Department of Physiology and Akira Sonoda at the Core Instrumentation Facility, Keio University School of Medicine.

Author Contributions
S.Y., R.M. and S.S. designed and performed the experiments. S.Y. and R.M. wrote the manuscript. K.H., T.M. and S.H. helped to edit the main manuscript.

Additional Information

Supplementary information accompanies this paper at http://www.nature.com/srep

Competing financial interests: The authors declare no competing financial interests.

How to cite this article: Yamaguchi, S. et al. Generation of kidney tubular organoids from human pluripotent stem cells. Sci. Rep. 6, 38353; doi: 10.1038/srep38353 (2016).

Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This work is licensed under a Creative Commons Attribution 4.0 International License. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in the credit line; if the material is not included under the Creative Commons license, users will need to obtain permission from the license holder to reproduce the material. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/