Involvement of nephrin in human placental trophoblast syncytialization

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Abstract

The placenta has numerous functions, such as transporting oxygen and nutrients and building the immune tolerance of the fetus. Cell fusion is an essential process for placental development and maturation. In human placental development, mononucleated cytotrophoblast (CTB) cells can fuse to form a multinucleated syncytiotrophoblast (STB), which is the outermost layer of the placenta. Nephrin is a transmembrane protein that belongs to the Ig superfamily. Previous studies have shown that nephrin contributes to the fusion of myoblasts into myotubes in zebrafish and mice, presenting a functional conservation with its Drosophila ortholog sticks and stones. However, whether nephrin is involved in trophoblast syncytialization remains unclear. In this study, we report that nephrin was localized predominantly in the CTB cells and STB of human placenta villi from first trimester to term pregnancy. Using a spontaneous fusion model of primary CTB cells, the expression of nephrin was found to be increased during trophoblast cell fusion. Moreover, the spontaneous syncytialization and the expression of syncytin 2, connexin 43, and human chorionic gonadotropin beta were significantly inhibited by nephrin-specific siRNAs. The above results demonstrate that nephrin plays an important role in trophoblast syncytialization.


Introduction

The syncytialization of trophoblast cells is a key event in human placental morphogenesis. Syncytialization occurs around the time of embryo implantation and continues until delivery. Primary syncytialization is a process in which trophoderm cells at the embryonic pole of the blastocyst fuse intercellularly and form a multinucleated syncytiotrophoblast (STB) that adheres to and penetrates the maternal uterine epithelium; this event is crucial for a successful embryo implantation (Red-Horse et al. 2004). After the blastocyst is fully covered by the maternal uterine epithelium and the placental villi are formed, the STB changes its function and stops invasion. Instead, it develops into the outermost layer of the placental villi, where it directly contacts maternal blood. During the remaining stages of pregnancy, the STB plays important functions in immune tolerance, the production of hormones such as human chorionic gonadotropin beta (β-hCG) and the exchange of nutrients and waste products (Malassine & Cronier 2002, Leisser et al. 2006, Huppertz & Borges 2008). In the so-called secondary syncytialization, mononucleated cytotrophoblast (CTB) cells lining the placental villi fuse with the multinucleated STB. Fusion and communication between the CTB cells and STB is fundamental for placentation and for a successful pregnancy (Gauster et al. 2010).

Cell fusion appears in a wide variety of organisms and in many cellular processes, such as yeast mating, Caenorhabditis elegans epidermal cell fusion, myotube formation, fertilization, macrophage fusion, tumorigenesis, and placentation (del Campo et al. 2005, Chen & Olson 2005). A number of proteins have been implicated in the fusion process. Syncytin proteins function as fusogens during trophoblast cell fusion through binding with their receptors (Blond et al. 2000, Mi et al. 2000, Blaise et al. 2003, Esnault et al. 2008). Connexin 43, ADAM12, CD98, and cadherin 11, all have been demonstrated to play the important roles in trophoblast cell–cell membrane merging (Getzios & MacCalman 2003, Mori et al. 2004, Dunk et al. 2012). Other factors which are involved in trophoblast cell fusion include proteases (caspases 8, 10, and 14), cytokines (LIF, MIC1, and TNFα), growth factors (VEGF, CSF, and EGF), and transcription factors (GCM1, Mash-2, and Twist)
(Yusuf et al. 2002, Baczyk et al. 2009, Butler et al. 2009, Huppertz & Gauster 2011). Disturbances in syncytial trophoblast differentiation or maintenance may lead to pregnancy disorders such as intraterine growth restriction and pre-eclampsia. However, the mechanisms governing syncytial fusion remain poorly understood.

Nephrin is the protein product of the NPHS1 gene, which belongs to the Ig superfamily. Nephrin has been found to be highly expressed in the kidney glomerulus (Lenkkeri et al. 1999). As a transmembrane protein, nephrin has a short intracellular domain and a large extracellular domain with eight distal Ig-like motifs (Kestila et al. 1998). Nephrin is a central component of the slit diaphragm in glomerular podocytes (Ruotsalainen et al. 1999). The cell adhesion activities of nephrin have been confirmed in kidney podocytes and HEK-293 cells (Khoshnoodi et al. 2003, George et al. 2012). It is well established that nephrin plays a critical role in the renal ultrafilter. However, little is known about the potential roles of nephrin in extra-renal tissues. Sticks and stones (Sns), the Drosophila ortholog of nephrin, functions as a positive regulator of myoblast fusion and is also required for the adhesion and fusion of insect nephrocytes (Zhuang et al. 2009). Nephrin also has a conserved function in the fusion of zebrafish and mouse myoblasts. Indeed, it has been shown that nephrin mRNA is upregulated in nascent myotubes, and the total amount of myoblast fusion is decreased in nephrin-knockout mice compared with the WTone (Sohn et al. 2009). Therefore, nephrin is critical for the fusion of myoblasts into nascent myotubes (Sohn et al. 2009). So far as we know, there is no report on the expression of nephrin during the fusion of primary human CTB cells and BeWo cells, which are well-characterized models of human placental trophoblast syncytialization. Given its conservative and critical role in myoblast fusion, we hypothesized that nephrin may also play a role in human trophoblast syncytialization.

In this study, we first investigated the expression of nephrin in different human trophoblast cells from first, second, and third trimester placentas. Using a spontaneous syncytialization model of primary CTB cells, we observed increased expression in both nephrin mRNA and protein during the process of syncytialization. Furthermore, the spontaneous syncytialization of primary CTB cells and the expression of syncytin 2, connexin 43, and β-hCG were significantly inhibited when nephrin was silenced. And the expression of β-hCG was significantly elevated in nephrin stably overexpressed BeWo cells. The above evidence strongly supports a role for nephrin in human trophoblast syncytialization.

Materials and methods

Tissue collection

Human placental villi and term tissues from healthy 27- to 31-year-old women were collected from 301th Hospital of People’s Liberation Army with written consent. Approval to obtain and use these samples for this study was in accordance with the Ethics Committee of the 301th Hospital of People’s Liberation Army and the Institute of Zoology at the Chinese Academy of Sciences. For immunohistochemistry and western blotting, nine normal placental tissues at different gestational stages (three from the first trimester, three from the second trimester, and three at term) were used from women who underwent legal abortion or normal delivery. After being washed three times in PBS, the villi were fixed in 4% paraformaldehyde (PFA) for 24 h at 4 °C and kept in 70% ethyl alcohol until processing.

Isolation of primary CTB cells

The isolation of CTB cells from human term placentas was performed as described previously (Zhou et al. 2013). The placentas were cut into pieces and digested in DMEM (HyClone, Thermo Scientific, DuBouque, IA, USA) with 0.125% trypsin (Sigma–Aldrich, Inc.) and 0.02% DNase I (Sigma) four times. The supernatant was centrifuged for 15 min at 1200 g to obtain the cell pellets, which were separated by Percoll (GE Healthcare BiSciences AB, Uppsala, Sweden) density gradient centrifugation. The discontinuous 5–65% Percoll gradients were made from 3 ml of 90% Percoll and 1 ml of HBSS mixtures. CTB cells were purified in a 30–50% Percoll density gradient. CTB cells were seeded in 35 mm dishes (2 x 10^5/dish) in IMDM (HyClone) with 10% fetal bovine serum (FBS; Gibco BRL), 100 units/ml penicillin, and 100 units/ml streptomycin and cultured in a 5% CO2 air incubator at 37 °C.

BeWo cell culture and fusion assay

The human choriocarcinoma cell line BeWo was maintained in Ham’s F-12K (Kaighn’s; Gibco BRL/DMEM supplemented with 10% FBS, 100 U/ml penicillin, and 100 mg/ml streptomycin in 5% CO2/95% air at 37 °C. Cell fusion was induced by treating BeWo cells with forskolin (FSK, Sigma–Aldrich, Inc.) for 48 h. The achievement of cell fusion was assessed by two methods. First, immunofluorescence using anti-human E-cadherin antibody (sc-71008; Santa Cruz Biotechnology) for 48 h. The achievement of cell fusion was assessed by two methods. First, immunofluorescence using anti-human E-cadherin antibody (sc-71008; Santa Cruz Biotechnology) showed the loss of cell membrane during the fusion process. The number of multinucleated cells was counted in five randomly selected areas under the microscope. In addition, whole cell lysates of BeWo cells subjected to cell fusion induction exhibited increased levels of β-hCG, as shown by western blotting analysis.

Total RNA extraction and real-time PCR

Total RNA was extracted using TRIzol reagent according to the manufacturer’s instructions (Invitrogen). Two micrograms of RNA were reverse transcribed using Superscript II reverse transcriptase (Invitrogen) with oligo (dT) as primers. Real-time PCR was performed by using a SYBR Premix Ex Taq PCR Kit (Takara Biotechnology Co. Ltd, Dalian, China) on an ABI Prism 7500 Real-Time PCR System. Specific primers used were as follows: GAPDH, forward, 5’-GGATGTGGATGTGAACGGGTC-3’ and reverse, 5’-AGTGTCAGGTCAATACCCAGC-3’; β-hCG,
forward, 5'-GAGCTCACCAGCATCTATCACC-3' and reverse, 5'-TGGATGGGGGCGACCCTGG-3'; and nephrin, forward, 5'-TACCGGTTGTCCTGTCCT-3' and reverse, 5'-GCACCTGGGGAAAGGTGAC-3'.

Western blotting analysis
The cells were washed three times with cold PBS and mixed with whole-cell lysis buffer (4 mM EGTA, 3 mM EDTA pH 8.0, 125 mM NaF, 0.5 mM Na2VO3, 2.5 µg/ml aprotinin, 25 µg/ml trypsin inhibitor, 12.5 mM HEPES pH 7.4, 1% Triton X-100, and 25 µM phenylmethylsulphonyl fluoride) as described previously (Zhang et al. 2013). A BCA Protein Assay Kit (Pierce Biotechnology, Thermo Scientific, Dubuque, IA, USA) was used to determine the protein concentration by spectrophotometry at 562 nm (Beckman DU530, Fullerton, CA, USA). Twenty-five micrograms of each protein sample was subjected to western blotting analysis with the following primary antibodies: rabbit polyclonal anti-nephrin (1:500; ab58968, Abcam, Cambridge, MA, USA), rabbit polyclonal anti-human β-hCG (1:1000; ab54410, Abcam), mouse monoclonal anti-E-cadherin (1:1000; TA-09, Zhongshan Golden Bridge Crop., Beijing, China), rabbit polyclonal anti-Synaptophysin 2 (1:500; AP13018A, Abgent, San Diego, CA, USA), mouse monoclonal anti-b-actin (1:2000; TA-09, Zhongshan Golden Bridge Crop., Beijing, China), and rabbit polyclonal anti-Synaptophysin 2 (1:500; AP13018A, Abgent, San Diego, CA, USA), mouse monoclonal anti-nectin 43 (1:1000; 610061, Transduction Laboratories, Lexington, KY, USA), and HRP-conjugated secondary antibodies. Signals were detected by the GeneGnome Imaging System (Syngene Bio-imaging, Cambridge, UK).

Nephrin stable overexpression in BeWo cells
A full-length human nephrin coding sequence was generated by PCR from a pCMV-SC-CF plasmid (a kind gift from Puneet Garg at University of Michigan School of Medicine, Ann Arbor, MI, USA). Nephrin was cloned into a pGEM-T vector (Promega) and subcloned into a CSII-CMV-MCS-IRES2-Venus vector using the NheI and NotI sites. The lentivirus vectors were kindly provided by Dr Hiroyuki Miyoshi (Riken BioResource Center, Tsukuba, Japan). All of the lentiviral vectors were generated by transient transfection of 293T cells using the calcium phosphate precipitation method. Briefly, 293T cells were seeded into 100 mm dishes with DMEM medium containing 10% FBS. The mixture of the main plasmid and the packaging plasmids was transfected into each dish by calcium phosphate precipitation method. The cells were washed three times for 5 min each. The cells were then incubated with anti-mouse Alexa Fluor 555 (Invitrogen) secondary antibody for 1 h at room temperature. The nuclei of the CTB cells were stained with 4',6-diamidino-2-phenylindole (DAPI). To quantify primary CTB cells syncytialization without bias, three different nonoverlapping fields were randomly selected for each time point under the microscope. The fusion index was calculated using the formula of (N−S)/T, where N is the number of nuclei in the syncytia, S is the number of syncytia, and T is the total number of nuclei (Matsuura et al. 2011). All experiments were performed in triplicate and the results are presented as means ± S.E.M.

Immunofluorescence
Primary CTB cells were rinsed in PBS and fixed. After blocking with 5% donkey serum for 20 min, the slides were incubated with monoclonal anti-E-cadherin (1:100; sc71008, Santa Cruz Biotechnology) overnight at 4°C with primary antibodies against nephrin (1:150; ab58968, Abcam), cytokeratin 7 (1:200, ZM-0071, Zhongshan Golden Bridge Crop.) or β-hCG (1:200, ZM-0134, Zhongshan Golden Bridge Crop.). Purified Igs (IgG) from rabbit or mouse were used as negative controls.

RNA interference
The cells were seeded at 2 × 10⁶ cells into 35 mm dishes. One-hundred nanomolar nephrin-specific siRNA (Invitrogen; 5'-CUU CCA AUA UCA UCA A3' and 5'-CUU CCA AUA UCA UCA A3') or negative control siRNA (5'-UUC UCC GAA CGU GUC UCG A3') was diluted in OPTI-MEM and transfected with Lipofectamine 2000 transfection reagent (Invitrogen) according to the manufacturer’s recommendations for 6 h. The effect of siRNAs on nephrin levels at 72 h after transfection was detected by real-time PCR and western blotting.

Statistical analysis
Each experiment was repeated three times. Data are presented as the mean ± S.E.M. One-way ANOVA and t-tests were used for statistical analyses with P < 0.05 being considered as significant.

Results
Expression of nephrin in human placentas at different stages of pregnancy
To examine the expression of nephrin during human placentation, we carried out immunohistochemistry on placental tissues from the first, second, and third trimesters. CK7, an epithelial marker, was used to
immunolabel CTB cells, extravillous trophoblast cells in the trophoblast cell column or cells which invaded into the maternal decidua (d and d'), while β-hCG specifically immunostained the STB layer (c and c'). As shown in Fig. 1A, B and C, nephrin was highly expressed in both the CTB cells and STB from first to third trimesters (b and b'). Control sections using normal IgG instead of a primary antibody exhibited no specific staining, as is representatively shown in a and a'.

Validation of spontaneous syncytialization of primary CTB cells

To elucidate the function of nephrin in placentation under physiological conditions, we first set up a model for spontaneous syncytialization of primary CTB cells. We isolated fresh CTB cells from human term placenta and obtained a population of cells, more than 95% of which were CK7-positive (data not shown). We cultured the cells in vitro for 72 h. During this period of time, mononucleated CTB cells spontaneously fused and formed multinucleated syncyitia. As shown in Fig. 2A, most cells were mononucleated at 0 h and showed clear E-cadherin immunostaining on their cell membranes. Some syncyitia appeared at a 24-h culture with multiple nuclei in a single cell boundary (arrow). At 48 and 72 h, large syncyitia with more than ten nuclei appeared abundantly (arrow). The fusion index was also increased with the process of spontaneous syncytialization (Fig. 2B; P < 0.05); at 72 h of culture, ~76% of the cells fused and ended up as multinucleated syncyitia. Message levels of β-hCG were significantly increased (over 1000- and 2000-fold at 48 and 72 h respectively) during spontaneous fusion of primary cells (Fig. 2C; P < 0.05 as compared with 0 h). Western blotting analysis showed that protein levels of syncytin 2, connexin 43, and β-hCG were also elevated (Fig. 2D).

Nephrin expression was increased during the spontaneous syncytialization of primary CTB cells

Next, the expression of nephrin mRNA and protein levels during the syncytialization of primary CTB cells was examined by real-time PCR and western blotting using RNA and protein samples harvested at 0, 24, 48, and 72 h of syncytialization. As shown in Fig. 3A, the level of nephrin mRNA was low at 0 and 24 h, but was markedly increased at 48 h and then slightly decreased at 72 h of culture (P < 0.05 as compared to 0 h). Furthermore, nephrin protein levels showed a similar expression profile (Fig. 3B).

Requirement of nephrin in the fusion of primary CTB cells

To further assess the function of nephrin in the fusion of primary CTB cells, we used two different siRNAs specifically targeting nephrin to silence the expression in CTB cells. As shown in the Fig. 4A, the level of β-hCG mRNA was decreased by ~40% (P < 0.05) upon nephrin siRNA1 knockdown. Western blotting analysis showed that the expression levels of syncytin 2, connexin 43, and β-hCG were decreased when silencing nephrin (Fig. 4B). Immunofluorescence showed that E-cadherin staining disappeared in the negative-control siRNA group (Fig. 4C, left panel), but in the nephrin-silenced group, E-cadherin staining was clearly visible on mononucleated trophoblast cell membranes (Fig. 4C, right panel), and more mononucleated cells were present compared with cells treated with the negative control siRNA. Statistical analysis of the fusion index after nephrin silencing showed that the efficiency of
syncytialization in the nephrin siRNA group was less than that of the negative control siRNA group (Fig. 4D, \( P < 0.05 \)).

**Nephrin overexpression promoted β-hCG expression in BeWo cells**

To further prove whether there might be a positive relationship between nephrin expression and syncytialization, we constitutively overexpressed nephrin in BeWo cells. Western blotting analysis of the nephrin-overexpressed BeWo cells showed that levels of β-hCG were increased, as indicated in Fig. 5A and B (\( P < 0.05 \)). Moreover, the fusion index of the nephrin-overexpressed cells was higher than that of the cells transfected with an empty vector (Fig. 5C).

**Discussion**

This study suggests that nephrin is involved in trophoblast syncytialization based on the following observations. First, nephrin was expressed in human CTB cells and STB in placentas from the first, second, and third trimesters. Both nephrin mRNA and protein levels were dramatically increased during the spontaneous syncytialization of primary human CTB cells. Moreover, knockdown of nephrin by siRNA not only reduced the number of syncytia, but also decreased the expression of syncytin 2, connexin 43, and β-hCG. Membrane merging is critical for cell–cell fusion. Indeed, the discovery of syncytins is a milestone in the understanding of human syncytialization. The syncytin family includes syncytin 1 and 2 in humans and syncytin A and B in mice (Dupressoir et al. 2005, Lavialle et al. 2013), which are one of the two groups of proteins that are called fusogens in the cell–cell fusion process. The other family of fusogens includes EFF1 and AFF1, which have been discovered in C. elegans (Mohler et al. 2002, del Campo et al. 2005, Sapir et al. 2007). In addition to the above-mentioned fusogens, the expression of connexin 43, a hexamer from which gap junctions are comprised, is increased during the differentiation of CTB cells (Dunk et al. 2012), while the expression of zona occludens-1, an adherens junction protein that ‘zips’ cells together, is predominantly present during CTB cells aggregation but is significantly decreased upon cell fusion (Pidoux et al. 2010). Calponin 3 (CNN3), a CNN family member, is also a negative regulator of trophoblast fusion (Shibukawa et al. 2010). CD98 and its proposed ligand, galectin-3, may play a positive role in promotion of syncytialization (Mori et al. 2004). Our previous studies have shown that the proprotein convertase furin is required for trophoblast...
interacts with SH2–SH3 domain-containing adapter Nck defects in zebrafish and mice. Interestingly, nephrin regulation of nephrin expression results in muscle efficiently into nascent human myotubes, and down-
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regulation of nephrin expression results in muscle
defects in zebrafish and mice. Interestingly, nephrin
interacts with SH2–SH3 domain-containing adapter Nck
to regulate actin cytoskeletal dynamics in podocytes
(Verma et al. 2006), and in myoblast fusion, the
appearance of actin foci is obligatory for fusion (Onel
& Renkawitz-Pohl 2009, Haralalka et al. 2011). Coexpression of Sns and EFF1 can induce highly efficient
cell fusion in Drosophila S2R+ cells (Shilagardi et al.
2013). Our study adds a new function for nephrin during
primary trophoblast syncytialization, which is accom-
panied by the increase in important fusion-related
molecules, including syncytin 2, connexin 43, and
β-hCG. When the expression of nephrin was knocked
down, trophoblast syncytialization as well as the
expression of syncytin 2 and connexin 43 was
decreased. In the placenta, syncytin is located on the
cell membrane and mediates placental CTB cell fusion
by binding to the syncytin receptor (Mi et al. 2000,
et al. 2009). As a gap junctional protein, connexin 43 is
required for CTB cell fusion into syncytia (Dunk et al.
2012, Pidoux et al. 2014). We therefore speculate that
nephrin may be involved in the syncytialization
machinery via enhancing the expression of syncytin
and connexin 43, and the underlying mechanisms await
further study.

Aberrant fusion of the CTB cells with the STB will
impair the maintenance and integrity of the placental
barrier, which may thus be involved in pregnancy
disorders. Interestingly, it has been reported that serum
and urine concentrations of nephrin are associated with
pre-eclampsia and small for gestational age infants (Yang
et al. 2013). Therefore, nephrin may play a role in the
pathogenesis of proteinuria in pre-eclampsia. Further
investigation is necessary for elucidating the clinical

 syncytialization, and the expression of furin in the STB is
significantly lower in placentas from pre-eclampsia
patients (Zhou et al. 2013). In addition, the processing
of insulin-like growth factor 1 receptor (IGF1R) by furin
is necessary for trophoblast syncytialization (Zhou et al.
2013). E-cadherin levels are significantly increased
during earlier stages of syncytialization (Coutifaris et al.
1991). However, as syncytialization progresses, for
example, ~24 h later in culture in the spontaneous
syncytialization system, E-cadherin levels are decreased
(Coutifaris et al. 1991). In contrast, cadherin-11
expression increases during the formation of multi-
nucleated syncyta, and it promotes the morphological
and functional differentiation of human CTB cells
(Getsios & MacCalman 2003).

The expression of nephrin has been found in the
kidney, pancreas, brain, and lymphoid tissues (Putaala
et al. 2001, Astrom et al. 2006). Verma et al. (2006) have
observed that mutation or deletion of nephrin protein in
the slit diaphragm in the kidney leads to a defect in
donkey foot process morphogenesis, and that protei-
nuria is the clinical symptom. Sohn et al. (2009) have
confirmed that nephrin knockout myoblasts fuse less
efficiently into nascent human myotubes, and down-
regulation of nephrin expression results in muscle
defects in zebrafish and mice. Interestingly, nephrin
interacts with SH2–SH3 domain-containing adapter Nck

downregulated after nephrin knockdown. (C) Immunofluorescence
images of primary human CTB cells transfected with nephrin siRNA
(right) or negative control siRNA (left). More mononucleated cells
appear in the nephrin siRNA-transfected group compared with the
negative control siRNA group (*mononucleated cell). (D) Bar graph of
the fusion index after silencing nephrin (*P<0.05).

Figure 4 Silencing nephrin inhibits syncytialization in primary CTB
cells. Primary human CTB cells were transfected with negative control
siRNA or nephrin siRNA1 or 2 (n=3). (A) Approximately 60% of
nephrin mRNA is knocked down by siRNA1 (n=3; *P<0.05).
(B) Expression of syncytin 2, connexin 43, and β-hCG is significantly
downregulated after nephrin knockdown. (C) Immunofluorescence
images of primary human CTB cells transfected with nephrin siRNA
(right) or negative control siRNA (left). More mononucleated cells
appear in the nephrin siRNA-transfected group compared with the
negative control siRNA group (*mononucleated cell). (D) Bar graph of
the fusion index after silencing nephrin (*P<0.05).

![Figure 4](image1)

Nephrin overexpression promotes β-hCG expression in BeWo
cells. Nephrin stably overexpressed BeWo cells and control BeWo cells
were incubated in a medium with or without 50 μM FSK for 48 h.
(A) Western blotting analysis shows that levels of β-hCG protein are
increased in nephrin overexpressed cells compared with control cells.
(B) Bar graph of β-hCG band density (*P<0.05). (C) Bar graph of the
fusion index after nephrin overexpression in BeWo cells.

![Figure 5](image2)
significance of placental nephrin in pregnancy-related diseases. Taken together, we herein demonstrate a new function for nephrin in promoting the syncytialization of human trophoblast cells.

Declaration of interest
The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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