

Royal Society Stem Cells

iPS cells; opportunities and challenges

Keisuke Okita¹ & Shinya Yamanaka^{1,2*}

¹ Center for iPS Cell Research and Application (CiRA), Kyoto University, Kyoto
606-8507, Japan

² Gladstone Institute of Cardiovascular Disease, San Francisco, CA 94158

* To whom correspondence should be addressed:

Shinya Yamanaka, Center for iPS Cell Research and Application (CiRA), Kyoto
University, 53 Kawahara-cho, Shogoin, Sakyo-ku, Kyoto 606-8507, Japan. Phone:
+81-75-751-3839, Fax: +81-75-751-4632, e-mail: yamanaka@cira.kyoto-u.ac.jp

Abstract

Somatic cells have been reprogrammed into pluripotent stem cells by introducing a combination of several transcription factors, such as Oct3/4, Sox2, Klf4, and c-Myc. Induced pluripotent stem (iPS) cells from a patient's somatic cells could be a useful source for drug discovery and cell transplantation therapies. However, most human iPS cells are made by viral vectors, such as retrovirus and lentivirus, which integrate the reprogramming factors into the host genomes and may increase the risk of tumor formation. Several non-integration methods have been reported to overcome the safety concern associated with the generation of iPS cells, such as transient expression of the reprogramming factors using adenovirus vectors or plasmids, and direct delivery of reprogramming proteins. Although these transient expression methods could avoid genomic alteration of iPS cells, they are inefficient. Several studies of gene expression, epigenetic modification, and differentiation revealed the insufficient reprogramming of iPS cells, thus suggesting the need for improvement of the reprogramming procedure not only in quantity but also in quality. This report will summarize the current knowledge of iPS generation and discuss future reprogramming methods for medical application.

Introduction

Reprogramming has been studied extensively for decades. Nuclear transfer into an oocyte gives somatic cells pluripotency to produce cloned animals. For example, Dr. J. Gurdon and his colleagues showed that frog somatic cell nuclei can be reprogrammed after transferred into enucleated oocytes, and they develop into feeding tadpoles (1). Reprogramming in vertebrates was also proven by the creation of cloned animals from sheep (2) and mice (3). In addition to oocytes, human(4) and mouse ES(5) cells also can reprogram somatic cells into an ES cell-like state after cell fusion. These results demonstrated that terminally differentiated cells can revert to a state of pluripotency in response to external stimulation.

The accumulated understanding of the mechanisms underlying pluripotency in ES cells led to attempts to revert somatic cells into a pluripotent state using defined factors. Twenty-four candidate factors were transduced into mouse embryonic fibroblasts by retroviral delivery and this identified four factors that can convert fibroblasts into induced pluripotent stem cells (iPSC)(6). iPS cells have been generated from mouse (6), rat (7, 8), monkey (9), pig (10), dog (11), rabbit (12) and human (13, 14). Most of the iPS cells are derived using the OCT3/4, SOX2, Klf4, and c-Myc

reprogramming factors. The original iPS cell induction system used retroviral vectors, which integrate transgenes into the host genome. The insertion of tumorigenic genes, like c-Myc, and activation of proto-oncogenes by LTR increase the risk of tumor formation (15, 16).

Mouse iPS cells were generated using a plasmid vector in 2008 and showed that iPS cells can be induced by the transient expression of reprogramming factors(17). The goals of those experiments were to increase transfection efficiency in primary cells and to maintain transgene expression long enough (a few weeks) for iPS cell induction. Three essential reprogramming factors (Oct3/4, Sox2, and Klf4) were connected in a single plasmid using the 2A sequence, which enables expression of multiple proteins from a single RNA transcript. The stoichiometric balance of these core transcription factors is thought to be important for iPS cell induction, and therefore all six possible orders of the factors in retrovirus system were examined to determine the most effective arrangement. The three factors were then placed into a plasmid vector with a constitutively active CAG promoter, which yielded high expression (18). This vector assures co-expression of the three core factors in all of the transfected cells. In addition, another expression vector for c-Myc was constructed. The transfection of the plasmids into mouse embryonic fibroblasts was repeated multiple times to achieve the sustained

expression required for iPS cell generation. iPS cell colonies we obtained after four weeks, albeit at a very low frequency. As expected, iPS cell clones in which transgenes had been integrated into the host genome were frequently observed. However, no transgene integration was detected in approximately one third of the established mouse iPS cell clones. The integration-free iPS cell clones have the potential to differentiate into various cell types of the three germ layers. Furthermore, they were able to form chimeric mice when transplanted into blastocysts, which were competent for germline transmission.

The frequency of iPS cell generation by plasmids, however, was very inefficient. The estimated efficiency is less than 0.0002%, which is at least 1000-fold lower than that of viral induction. The fact that reprogramming efficiency of human fibroblasts with retrovirus is approximately 10-fold lower than that of mouse fibroblasts, suggested that the generation of integration-free human iPS cells would be extremely inefficient using the same method. Subsequently, several methods for integration-free human iPS cell generation have been reported. The approach can be divided into four groups based on delivery methods of the reprogramming factors; 1) virus(13, 19, 20), 2) DNA(21-24), 3) RNA(25), and 4) protein(26)(Table 1). We calculated induction efficiency of each method from the best result reported in the article. Because of the

difference of their experimental settings, it is hard to compare their efficiency correctly.

However, as predicted, non-integration methods are extremely inefficient in general.

Notably, recent reports showed significant improvement of non-integration method.

Sendai virus is a minus strand RNA virus. Fusaki et al. infected Sendai virus vectors encoding reprogramming factor into human fibroblasts and obtained iPS cells(20).

Because Sendai virus replicate its genome in the cytoplasm of infected cells, this vector system can stably express reprogramming factors and achieve high reprogramming efficiency. The established iPS cells, on the other hand, tended to carry on virus genome even after long time culture. To obtain viral-free cells, additional approach was needed such as the elimination of virus containing cells through negative selection against virus antigen, HN, or using temperature sensitive mutant. Direct delivery of synthetic mRNA also generated iPS cell at high efficiency(25). The mRNA sustained high and relatively long expression of encoding reprogramming factors by using modified ribonucleotides.

However reprogramming via modified RNAs is technically difficult, sensitive to reagents, and requires labor-intensive procedures. Therefore, further improvements in reprogramming methods are absolutely required for reproducible generation of integration-free human iPS cells. A summary of several topics associated with iPS cell generation and a discussion of the future in reprogramming methods for medical and

other applications are herein provided.

Myc family

c-Myc is a potent inducer of reprogramming(27). Its functions are not fully understood; however, one of the functions may be direct activation of pluripotent marker genes.

Though c-Myc is ubiquitously expressed in several cell types, it has essential function for maintenance of the pluripotent state in mouse ES cells. Mouse ES cells can be maintained by activation of the STAT3 signal through addition of its upstream cytokine, leukemia inhibitory factor (LIF). Dalton and colleagues showed that c-Myc is one of STAT3 target genes and that forced expression of c-Myc alone can keep mouse ES cells in a pluripotent state (28). Both c-Myc and N-Myc inhibit differentiation of mouse ES cells into the primitive endoderm lineage, through suppression of Gata-6 expression, the master gene (29). Interestingly, the incorporation of c-Myc in the reprogramming cocktail promoted the frequency of germ-line transmission from chimeric mice in comparison to iPSCs generated without the Myc transgenes (30). Therefore, c-Myc affects the net reprogramming process. Another role of c-Myc is acceleration of the cell cycle, although it activates the p53 and p21 pathway. More than 4000 sites in the genome are reported as c-Myc binding regions (31). Myc binding may loosen chromatin

structure and facilitate the access of other reprogramming factors to their target sequences. c-Myc enhances iPS cell generation at least in part through these mechanisms; on the other hand its tumorigenic properties could have inhibitory effect on proper reprogramming and increase the frequency of transformed cells during iPS generation. Myc also increases the risk of tumor formation when the transgene remain in established iPS cells(15).

The Myc family consists of three genes; c-Myc, N-Myc, and L-Myc. All members form heterodimers with Max protein and bind to target DNA. Their entire amino acid sequences are similar; however, L-Myc is shorter in the N-terminal region than the other two members. Interestingly, the N-terminal region contributes to transformation activity in cultured cells. Consistent with this, activation of L-Myc in human tumors are less frequently reported. Therefore L-Myc was the candidate for a reprogramming enhancer without increasing the tumorigenic risk. Therefore, attempts were made to use L-Myc for iPS cell induction(30). Using L-Myc for the induction of mouse iPS cells increases the number of iPS cell colonies in comparison to cells transduced with Oct3/4, Sox2, and Klf4, however, the effect was weaker than for c-Myc. L-Myc showed less colony formation than c-Myc which results in a higher ration of iPS cell colonies among the total number of colonies. In contrast, L-Myc enhanced iPS

induction more efficiently than c-Myc in human fibroblasts. c-Myc and N-Myc markedly increased the formation of non-iPSC colonies, whereas L-Myc did not. Therefore, the proportion of human iPS colonies in of the total colonies is significantly higher with L-Myc than with c-Myc or N-Myc. Therefore, different functional moieties of the Myc proto-oncogene products are involved in the transformation and promotion of directed reprogramming. A microarray analysis has shown the enhancing effect of L-Myc on reprogramming to be predominantly accomplished by the suppression of fibroblast-specific genes. In addition, L-Myc activates showed weaker activation of genes related to tumor formation than did c-Myc. These data demonstrated that L-Myc may therefore be more suitable for human iPS cell generation than c-Myc.

p53

The expression of pluripotent marker genes are often found in immature tumor cells. For example, breast cancer cells show elevated level of Oct3/4 and Sox2(32, 33). In addition, these cancer stem cells have a differentiation potential to transform into several cell types. Both immature tumor cells and iPS cells are derived from somatic cells and obtain differentiation potential. These similarities suggest an underlying common mechanism of reprogramming toward iPS cells and cancer cells and led to an

examination of the roles of the tumor suppressor gene, p53, during iPS cell generation(34). A relationship between the p53 pathway, c-Myc and Klf4 has also been reported. The transduction of p53-null MEF with the four reprogramming factors revealed marked enhancement of iPS cell colony formation. They formed tightly packed compact colony, similar to ES cells. They also express pluripotent marker genes including Nanog and ECAT1. The injection of these reprogrammed cells into immuno-deficient mice results in the formation of teratomas containing various cell types of the three germ layers, such as neuronal tissue, cartilage, muscle, and gut-like epithelium. Their pluripotency was further confirmed by chimeric mouse formation. Enhancement of reprogramming was also observed by induction of dominant negative form of p53 or its shRNA into wild-type human adult dermal fibroblasts. These data demonstrated that the loss of p53 markedly accelerates both mouse and human iPS cell generation.

p53 have many cellular functions, including regulation of apoptosis and senescence through p21. c-Myc stimulates p53 and then p21 during iPS cell generation, which both inhibit the reprogramming process. The forced expression of MDM2 increases reprogramming efficiency thorough the inhibition of p53. On the other hand, p53 suppression may lead to genomic instability; thus continuous suppression should be

avoided(35). It is important to carefully examine the genomic mutations and tumorigenicity of established iPS cell clones.

The cell cycle seems to play important roles during generation of iPS cells. Some of the reprogramming steps are likely to depend on stochastic events, such as the initial cell condition, microenvironment, fluctuation of gene expression and epigenetic modification. Therefore, an increase in the cell numbers simply increases the chance of iPS cell induction. Hanna et al. examined the relationship between cell number and reprogramming efficiency using the secondary induction system (36). They argued that reprogramming is a continuous stochastic process where almost all mouse donor cells eventually give rise to iPS cells after extended cultivation. Inhibition of the p53 and p21 pathway as well as the expression of Lin28 increases iPS cell generation predominantly by acceleration of the rate of cell division. On the other hand, an overexpression of Nanog seemed to enhance reprogramming in a proliferation independent manner.

LIN28

LIN28 is a negative regulator of the Let7 miRNA family. Lin28 induces the uridylation of immature let7 RNA by a non-canonical poly (A) polymerase, TUTase4, which leads degradation of the RNA(37). Lin28 gradually decreases during ES cell differentiation,

and mature let-7 family miRNAs becomes detectable with an inverse correlation. The targets of mature let7 include oncogenic genes, such as K-Ras and c-Myc. This is consistent with the analysis performed by Hanna et al. which showed that Lin28 accelerates the efficiency of iPS cell generation in a cell cycle dependent manner. However, Lin28 also facilitates the expression of Oct4 at the post-transcriptional level by direct binding to its mRNA(38). In addition, let-7 family miRNAs promotes differentiation of breast cancer cells and inhibits their proliferation (39). Therefore Lin28 may facilitate iPS cell generation, not only in a cell cycle dependent manner, but also by promoting Oct4 expression and suppressing the differentiation through the inhibition of let-7 family microRNA. Addition of Lin28 enhances the reprogramming efficiency from both human and mouse fibroblasts. Further studies are required, however, to elucidate the precise mechanisms.

ESRRB

Estrogen receptor related beta (Esrrb) is an orphan nuclear receptor, which has a significant homology with estrogen receptors. ESRRB regulates transcription constitutively through the estrogen response elements or steroidogenic factor-1 response elements of target genes. The suppression of ESRRB in ES cells results in

morphological changes and differentiation, thus suggesting an important role in self-renewal (40, 41). Esrrb positively regulates the expression of the key pluripotency gene Nanog(42), and the overexpression of Esrrb allows for short-term ESC maintenance without the addition of exogenous LIF (Zhang et al., 2008). Esrrb is also capable of replacing KLF4 in somatic cell reprogramming from MEFs, but to the lesser extent(43). However, the roles of ESRRB in human iPS cell induction remain to be determined.

SALL4

Sall (Sal-like) 4 belongs to the Spalt (Sal) transcription factor family characterized by highly conservative C₂H₂ zinc-finger motifs. Knockdown of Sall4 in mouse ES cells results in the loss of the undifferentiated state and differentiation into trophoctoderm-like cells, suggesting that Sall4 contributes to self-renewal of ES cells(44, 45). Importantly, many binding sites of Sall4 overlap with those of Oct3/4, Sox2 and Nanog in ES cells, as determined by ChIP on chip analyses(46). These data suggest that Sall4 plays a pivotal role in pluripotency. Hence, the effect of Sall4 in iPS generation(47). Addition of Sall4 to the reprogramming factors increases the iPS colony number from MEFs. However, the ectopic expression of SALL4 showed variable

effects on iPS generation from HDF. Three out of seven lines of HDF showed more than 2-fold increment. On the other hand, no such effects were observed in other four lines. A possible cause of the effects of SALL4 on different HDF lines is the expression levels of endogenous SALL4. A fibroblast line from a 36-year-old female, which showed the strongest effect of the SALL4 transgene, had the lowest expression level of the endogenous SALL4. Therefore, the addition of Sall4 could be beneficial when trying to achieve iPS cell generation from cells with a low endogenous Sall4 expression.

UTF1

The expression of UTF1 (undifferentiated embryonic cell transcription factor 1) is restricted in ES cells, embryonic carcinoma cells, and primordial germ cells. UTF1 functions as a chromatin-associated transcriptional repressor with a dynamic behavior similar to core histones(48). Knockdown of UTF1 in ES cells and embryonic carcinoma cells results in a substantial delay or block to differentiation(49). UTF1 may also be important for proliferation. These data indicate a possible role for UTF1 in the maintenance of a specific epigenetic profile that is required for differentiation and proliferation of ES cells. Zhao et al. screened several candidate factors along with conventional factors (OCT3/4, SOX2, KLF4, and C-MYC) for their capacity to improve

reprogramming step, and found a dramatic increase by UTF1 addition(50). They also found an inhibitory effect of p53 for reprogramming. However, none of other candidates including NANOG, LIN28, DPPA4, DPPA5, ZIC3, BCL-2, h-RAS, TPT1, SALL2, NAC1, DAX1, TERT, ZNF206, FOXD3, and REX1, increased iPS cell colony formation dramatically in their culture conditions.

TBX3

Tbx3 is a transcription factor belonging to T-box family. Tbx3 regulates the expression of Nanog and Sox2, and is involved in the transcriptional network for the maintenance of pluripotency in mouse ES cells(51). The expression of Tbx3 is induced by the activation of the PI3K pathway, whereas inhibited by the MAPK signaling. Short hairpin RNA (shRNA) mediated loss-of-function assays indicated requirement of Tbx3 in ES cells(40). Addition of TBX3 in reprogramming factors seemed to improve quality of iPS cells(52). Mouse iPS cells induced by Tbx3 together with Oct3/4, Sox2, and Klf4 do not show any significant difference in global gene expression profile in comparison to iPS cells without Tbx3. However, incorporation of Tbx3 increases the frequency of germ-cell contribution and germ-line transmission when injected into early mouse embryos. Chromatin immunoprecipitation (ChIP)-sequencing revealed that the direct

regulatory targets of Tbx3 shares a large number of common binding sites with Oct4, Sox2, and Nanog(52). Tbx3 may increase the probability of fully reprogrammed cells in iPS cell population.

miRNA

miRNAs are small single-stranded RNAs (around 22 nt) that directly interact with target mRNAs through complementary base-pairing and inhibit translation of the target genes. miRNA would also modify gene expression at a transcriptional level. miRNAs involved in many features of cell properties, such as proliferation, apoptosis, and differentiation, by fine-tuning gene expression. miR-291-3p, miR-294 or miR-295 increase reprogramming efficiency from MEF(53). The three miRNAs share a conserved seed sequence, suggesting they work through common targets. They could be downstream targets of c-Myc, because the miRNAs did not enhance reprogramming efficiency in the presence of c-Myc transgene, and c-Myc binds the promoter region of the cluster. The miR-200 family also promotes iPS cell generation through enhancing MET (described below)(54).

Gene balance

The low efficiency of iPSC induction from somatic cells raises the possibility that the precise balance and/or amount of each transgene expression is important for reprogramming. Retrovirally induced, fibroblasts can integrate more than 10 copies of transgenes, and it is difficult to control the balance and their inserting position. Retroviral vectors preferentially integrate into the promoter regions of active loci, where the transgene expression level is affected by the flanking promoter and other elements. Dramatic epigenetic changes occur during the reprogramming process. This could influence endogenous promoter activities and retroviral expression. Therefore, the level and balance of retroviral/lentiviral transgene expression can change even after their integration. Papapetrou et al. tried to monitor these expression levels through the process using lentivirus vectors encoding different fluorescent protein connected with each reprogramming factor(55). They infected these vectors into human fibroblasts at various multiplicities of infection (MOI), and thus found the iPSC induction rate to be highly sensitive to the OCT3/4 dosage. A 3-fold increase of OCT3/4 improved the reprogramming efficiency up to 2-fold, whereas 3-fold reduction severely decreased iPS generation. Interestingly, excess addition of OCT3/4 transgene spoiled the enhancement. On the other hand, a change of the other three factor dosages inhibited the reprogramming process. The overexpression of some reprogramming factors, such as

Nanog, c-Myc and Klf4, can maintain a pluripotent state in mouse ES cells(56). On the other hand, the forced overexpression of Oct3/4 or Sox2 results in the differentiation of mouse ES cells(57). A small degree of imbalance can be compensated in the mutual regulation networks because these reprogramming factors constitute a transcriptional circuit and maintain their expression level. However, an excess amount of imbalance would be harmful for iPS cell generation and maintenance.

Culture conditions

iPS cells have been established in the medium for ES cells. The external signals, leukemia inhibitory factor and basic fibroblast growth factor are important factors for mouse and human ES cell maintenance, respectively. Wnt signaling also supports the self-renewal of ES cells. The Wnt3a signal is mediated by glycogen synthase kinase (GSK) 3 β . The absence of the Wnt signal causes GSK3 β to inactivate target genes, such as β -catenin and c-Myc, by phosphorylation and proteasome-mediated degradation. Hence, the inhibition of GSK3 β with a chemical drug, CHIR99021, results in activation of Wnt signaling(8, 58). The addition of Wnt3a or CHIR99021 enhances the reprogramming efficiency both from mouse and human(8, 58). Kenpaullone, an inhibitor whose targets are GSK3 β as well as CDKs, can replace Klf4 when MEF are

transduced with Oct3/4, Sox2, and c-Myc (59). TGF-beta and BMP signals regulate MET and could also play an important role in the reprogramming process (described below)(54, 60).

O₂ tension is also an important aspect for stem cell maintenance and differentiation. For instance, low O₂ tension, hypoxia, promotes the survival of neural crest cells and hematopoietic stem cells, and prevents differentiation of human ES cells(61). Therefore, iPS cell induction performed in hypoxic conditions (5% O₂), shows up to 4-fold enhancement of the reprogramming efficiency in both mouse and human fibroblasts(62).

Epigenetic modifiers

Epigenetic modifying drugs can also improve iPS generation. For instance, inhibitors of DNA methyltransferase, such as 5'-azacytidine and RG108, increase reprogramming efficiency(63). A putative mechanism of active DNA demethylation was recently reported in a cell-fusion based reprogramming system(64). No consensus mammalian DNA demethylase has been identified. A complex consisting of a cytidine deaminase, AID, GADD45, and Mbd4, has been implicated in DNA demethylation(65). These factors function as an active demethylation complex by a coupled mechanisms of

AID-dependent deamination of 5-meC followed by thymine base excision by Mbd4.

AID is primarily known for its role in B cell class switch recombination and hypermutation in mammals. Fibroblasts have methylated DNA at the Oct3/4 promoter region. The activation and DNA demethylation of the Oct3/4 promoter occurs within 24 hours after cell fusion with ES cells. Bhutani et al. found that the suppression of AID by shRNA inhibits this promoter activation and DNA demethylation status in fused cells(64). AID is also involved in genome-wide erasure of DNA methylation in primordial germ cells(66). It is unclear whether AID also plays a role in the iPS cell induction process.

A global survey of DNA methylation in iPS cells and their parental origins (mostly fibroblasts) shows that iPS cells have rather higher DNA methylation than do their origins(67, 68). The upregulation of DNMT3b and DNMT3l occurs during the reprogramming process, and might be responsible for *de novo* methylation during iPS cell generation. The abnormal DNA methylation pattern including hypermethylation and hypomethylation can cause abnormal differentiation properties of iPS cells. Other epigenetic states, like histone methylation and acetylation, probably participate in iPS cell reprogramming. Addition of a histone deacetylase (HDAC) inhibitor, valproic acid (VPA), improves reprogramming efficiency in both mouse and human fibroblasts(69,

70). Other HDAC inhibitors, suberoylanilide hydroxamic acid and trichostatin A, also increase iPS cell generation from mouse fibroblasts(70).

Origin

iPS cells can have some memories of their parental sources. iPS cells from peripheral blood can differentiate into the hematopoietic lineage at a high efficiency(71). They did show a differentiation potential into neuronal cells, but the efficiency was low. However, iPS cells from different origins show markedly similar gene expression patterns in the undifferentiated state. Their clonal diversity is not beyond that of ES cells. Therefore, the memory could be epigenetic status at loci that are not directly related to the pluripotent status. Several differentially methylated DNA regions (DMR) have been reported(67). Although long-time passaging of iPS cells could largely attenuates these differences(72), studies of the relationship between DMR and differentiation potentials are needed to precisely evaluate iPS cells from different origins. The cell sources of iPS cells also influence the safety of the established iPS cells. The neural differentiation of mouse iPS cells derived from various tissues including MEF, tail-tip fibroblasts (TTF), hepatocyte, and stomach was performed to examine tumorigenicity(73). Clones that originated from TTF showed many residual pluripotent cells after three weeks of *in*

vitro differentiation into neural sphere, which resulted in teratoma formation when transplanted into an immune-deficient mouse brain. The precise mechanism of this phenomenon is yet to be determined, but it may be attributable to incomplete reprogramming, epigenetic memory and/or genomic stability. A “safe” iPS cell clone, showed therapeutic effects in a mouse model of spinal cord injury (74). The origin of iPS cells should also be important in human. It is important to consider clinically available sources. Human iPS cells have been generated from keratinocytes(75), mesenchymal cells in fat(76), oral mucosa (77), dental pulp cells(78), peripheral blood(79), and cord blood, in addition to skin fibroblasts(80). The properties and safety of these iPS cell clones should therefore be carefully examined.

Clone difference

Each human ES clone shows a distinct differentiation potential(81). Some tend toward the mesoderm lineage after embryoid body formation, but others prefer ectoderm differentiation. The characteristics of ES/iPS cells are also changed by culture conditions, such as growth medium, feeder cells, oxygen concentration, and passage methods(82). The culture time and passage number are particularly important with iPS cells, since reprogramming seems to continue even after establishment of iPS cell

colonies. Chin et al. reported that the continual cultivation of iPS cells yields a gene expression profile more similar to human ES cells than that of early passages(83). However, extended culture itself raises the risk of genomic instability. Some scientists believe that human ES/iPS cells in the naïve state have less diversity than that of those in the primed state. However, it is important to note that even mouse ES cells demonstrate diversity in their differentiation potential.

Naïve iPS cells

Pluripotent stem cells including iPS cells and ES cells are categorized into two groups by their morphology, gene expression profile, and external signal dependence.

Conventional mouse-type ES/iPS cells, which form compacted dome-shape colony in culture, are called “naïve state” cells. They are largely dependent on external LIF signals and show a high proliferation rate. On the other hand, human-type ES/iPS cells, which show flat colonies, are predominantly dependent on the bFGF signal, and proliferate more slowly, are termed “primed state”. Primed stem cells, called epiblast stem cells (EpiSC), can be established from mouse epiblasts with the addition of bFGF in culture medium(84, 85). The EpiSCs form flat colonies, and can differentiate into various cell types; however they fail to form chimeric mice when injected into

blastocyst. It could be due to the limited differentiation potential of the primed stem cells or just show the difference of their developmental stage. The addition of several transgenes such as OCT3/4 and KLF4 into conventional human iPS cells could successfully convert their status like mouse ES cells(86). These modified human iPS cells share several features with naïve stem cells, including morphology, growth properties, an X-chromosome activation state, a gene expression profile, and a signaling pathway dependence. However, the culture conditions of naïve human pluripotent cells seem not to be optimized, because they easily revert to the primed state. Further study should be performed to identify and establish stable handling methods for naïve human pluripotent stem cells.

Mechanisms underlying the reprogramming process

The reprogramming process has been gradually revealed by intense studies. Araki et al. traced the conversion of MEFs to iPS cells via a live cell imaging system(87). They introduced the reprogramming factors and observed MEFs dividing several times in a morphologically symmetric manner, maintaining a fibroblastic shape. Thereafter, the ancestral cells gradually transformed their morphology into an ES-like shape. The

transformation occurred within 48 hours after retroviral induction of the four factors in most cases. Importantly, their time-lapse analysis uncovered frequent failure in reprogramming at late stages of iPS induction. One of descendant becomes an iPS cell after an asymmetric division of reprogramming cells. However, the other descendant with the same retroviral insertion underwent cell death. The process was largely dependent on the c-Myc transgene. They frequently found the transient expression of GFP driven by the Nanog promoter. This unstable expression may indicate spontaneous activation of the locus, and may reflect stochastic events during reprogramming, which can be a stressful time for cells.

MEFs start to lose their mesenchymal character after the induction of transgenes, and then transform their shape into epithelial cells, the phenomenon known as the mesenchymal-to-epithelial (MET) transition(54, 60). MET is a biological process which often occurs during organ development. The molecular analysis revealed that reprogramming factors cooperatively induce MET in MEFs. Oct3/4 and Sox2 suppress Snail, a key factor of the epithelial-to-mesenchymal transition (EMT), which is the opposite of the MET. TGF-beta signals induce the EMT, at least in part, through the activation of Snail and thereby negatively regulate the MET. The c-Myc transgene enhances MET through the downregulation of TGF-beta signals by suppression of

TGF- β 1 and TGF- β receptor 2 expression. In addition, Klf4 upregulates genes associated with epithelial cells, such as E-cadherin. A temporal gene expression analysis revealed that the BMP signals promote the MET through the miR-200 family. The inhibition of MET by TGF- β signaling or by siRNA greatly reduced the reprogramming efficiency, suggesting that the MET is an important cellular event during reprogramming.

Chan et al. observed human iPS cell induction by live cell imaging in detail and found that there are three types of human iPS cells based on the expression profiles of cell surface markers and retroviral silencing(88). The three types differed in the methylation status of the promoter region of NANOG and OCT3/4 loci and their differentiation potential. The best reprogrammed type was positive for the pluripotency markers, SSEA-4 and TRA-1-60, and negative for the fibroblast marker, CD13, and showed inactivation of the retroviral promoter. Only this cell type could make teratomas containing tissues of all three germ layers. The discrimination of the high pluripotency cells from iPS cell induction cultures is necessary because the other two types of partially reprogrammed cells were morphologically similar to the correctly reprogrammed iPS cells.

Conclusion

Human iPS cells can be established with a variety of methods. There are several difference among 1) the cell source, 2) induction method, 3) reprogramming factors, 4) culture conditions including small molecular supplements, 5) type of stem cells (naïve or primed). Retro/lentiviral induction is sufficient for *in vitro* use of iPS cells when the remaining reprogramming factors do not significantly interrupt designed assays. However, the transgene integration and alteration of the endogenous genomic organization could cause a negative safety issue when considering medical applications. Genomic integration sites of retro- and lentivirus in iPS cells range from 1 to 40, and PCR-based analysis can detect all the integration sites. Hence, it may be possible to estimate their risk beforehand. Non-integration methods of iPS cell generation have been reported, but their induction efficiencies are quite low and may give rise to insufficiently reprogrammed iPS cells. These integration-free methods could be improved by using better combinations of reprogramming factors, better parental cell sources, and better culture conditions. The establishment of methods of iPS cell generation for clinical applications is an ongoing process. More comprehensive knowledge of the reprogramming process is therefore crucial for future clinical applications of iPS cells.

Reference

1. Gurdon JB. The developmental capacity of nuclei taken from intestinal epithelium cells of feeding tadpoles. *J Embryol Exp Morphol*. 1962 Dec;10:622-40.
2. Wilmut I, Schnieke AE, McWhir J, Kind AJ, Campbell KH. Viable offspring derived from fetal and adult mammalian cells. *Nature*. 1997;385(6619):810-3.
3. Wakayama T, Perry AC, Zuccotti M, Johnson KR, Yanagimachi R. Full-term development of mice from enucleated oocytes injected with cumulus cell nuclei. *Nature*. 1998;394(6691):369-74.
4. Cowan CA, Atienza J, Melton DA, Eggan K. Nuclear reprogramming of somatic cells after fusion with human embryonic stem cells. *Science*. 2005 Aug 26;309(5739):1369-73.
5. Tada M, Tada T, Lefebvre L, Barton SC, Surani MA. Embryonic germ cells induce epigenetic reprogramming of somatic nucleus in hybrid cells. *Embo J*. 1997 Nov 3;16(21):6510-20.
6. Takahashi K, Yamanaka S. Induction of pluripotent stem cells from mouse embryonic and adult fibroblast cultures by defined factors. *Cell*. 2006 Aug 25;126(4):663-76.
7. Liao J, Cui C, Chen S, Ren J, Chen J, Gao Y, et al. Generation of induced pluripotent stem cell lines from adult rat cells. *Cell Stem Cell*. 2009 Jan 9;4(1):11-5.
8. Li W, Wei W, Zhu S, Zhu J, Shi Y, Lin T, et al. Generation of rat and human induced pluripotent stem cells by combining genetic reprogramming and chemical inhibitors. *Cell Stem Cell*. 2009 Jan 9;4(1):16-9.
9. Liu H, Zhu F, Yong J, Zhang P, Hou P, Li H, et al. Generation of induced pluripotent stem cells from adult rhesus monkey fibroblasts. *Cell Stem Cell*. 2008 Dec 4;3(6):587-90.
10. Esteban MA, Xu J, Yang J, Peng M, Qin D, Li W, et al. Generation of induced pluripotent stem cell lines from tibetan miniature pig. *J Biol Chem*. 2009 Apr 21.
11. Shimada H, Nakada A, Hashimoto Y, Shigeno K, Shionoya Y, Nakamura T. Generation of canine induced pluripotent stem cells by retroviral transduction and chemical inhibitors. *Mol Reprod Dev*. 2009 Nov 4.
12. Honda A, Hirose M, Hatori M, Matoba S, Miyoshi H, Inoue K, et al. Generation of induced pluripotent stem cells in rabbits: potential experimental models for human regenerative medicine. *J Biol Chem*. 2010 Jul 29.

13. Takahashi K, Tanabe K, Ohnuki M, Narita M, Ichisaka T, Tomoda K, et al. Induction of pluripotent stem cells from adult human fibroblasts by defined factors. *Cell*. 2007 Nov 30;131(5):861-72.
14. Yu J, Vodyanik MA, Smuga-Otto K, Antosiewicz-Bourget J, Frane JL, Tian S, et al. Induced pluripotent stem cell lines derived from human somatic cells. *Science*. 2007 Dec 21;318(5858):1917-20.
15. Okita K, Ichisaka T, Yamanaka S. Generation of germ-line competent induced pluripotent stem cells. *Nature*. 2007 Jul 19;448:313-7.
16. Hacein-Bey-Abina S, Von Kalle C, Schmidt M, McCormack MP, Wulffraat N, Leboulch P, et al. LMO2-associated clonal T cell proliferation in two patients after gene therapy for SCID-X1. *Science*. 2003 Oct 17;302(5644):415-9.
17. Okita K, Nakagawa M, Hyenjong H, Ichisaka T, Yamanaka S. Generation of Mouse Induced Pluripotent Stem Cells Without Viral Vectors. *Science*. 2008 Nov 7;322(5903):949-53.
18. Niwa H, Yamamura K, Miyazaki J. Efficient selection for high-expression transfectants with a novel eukaryotic vector. *Gene*. 1991;108(2):193-9.
19. Zhou W, Freed CR. Adenoviral gene delivery can reprogram human fibroblasts to induced pluripotent stem cells. *Stem Cells*. 2009 Nov;27(11):2667-74.
20. Fusaki N, Ban H, Nishiyama A, Saeki K, Hasegawa M. Efficient induction of transgene-free human pluripotent stem cells using a vector based on Sendai virus, an RNA virus that does not integrate into the host genome. *Proc Jpn Acad Ser B Phys Biol Sci*. 2009;85(8):348-62.
21. Woltjen K, Michael IP, Mohseni P, Desai R, Mileikovsky M, Hamalainen R, et al. piggyBac transposition reprograms fibroblasts to induced pluripotent stem cells. *Nature*. 2009 Apr 9;458(7239):766-70.
22. Kaji K, Norrby K, Paca A, Mileikovsky M, Mohseni P, Woltjen K. Virus-free induction of pluripotency and subsequent excision of reprogramming factors. *Nature*. 2009 Apr 9;458(7239):771-5.
23. Jia F, Wilson KD, Sun N, Gupta DM, Huang M, Li Z, et al. A nonviral minicircle vector for deriving human iPS cells. *Nat Methods*. 2010 Mar;7(3):197-9.
24. Yu J, Hu K, Smuga-Otto K, Tian S, Stewart R, Slukvin, II, et al. Human induced pluripotent stem cells free of vector and transgene sequences. *Science*. 2009 May 8;324(5928):797-801.
25. Warren L, Manos PD, Ahfeldt T, Loh YH, Li H, Lau F, et al. Highly Efficient Reprogramming to Pluripotency and Directed Differentiation of Human Cells with Synthetic Modified mRNA. *Cell Stem Cell*. 2010.

26. Kim D, Kim CH, Moon JI, Chung YG, Chang MY, Han BS, et al. Generation of Human Induced Pluripotent Stem Cells by Direct Delivery of Reprogramming Proteins. *Cell Stem Cell*. 2009 Jun 5;4(6):472-6.
27. Nakagawa M, Koyanagi M, Tanabe K, Takahashi K, Ichisaka T, Aoi T, et al. Generation of induced pluripotent stem cells without Myc from mouse and human fibroblasts. *Nat Biotechnol*. 2008 Jan;26(1):101-6.
28. Cartwright P, McLean C, Sheppard A, Rivett D, Jones K, Dalton S. LIF/STAT3 controls ES cell self-renewal and pluripotency by a Myc-dependent mechanism. *Development*. 2005 Mar;132(5):885-96.
29. Smith KN, Singh AM, Dalton S. Myc represses primitive endoderm differentiation in pluripotent stem cells. *Cell Stem Cell*. 2010 Sep 3;7(3):343-54.
30. Nakagawa M, Takizawa N, Narita M, Ichisaka T, Yamanaka S. Promotion of direct reprogramming by transformation-deficient Myc. *Proc Natl Acad Sci U S A*. 2010 Aug 10;107(32):14152-7.
31. Li Z, Van Calcar S, Qu C, Cavenee WK, Zhang MQ, Ren B. A global transcriptional regulatory role for c-Myc in Burkitt's lymphoma cells. *Proc Natl Acad Sci U S A*. 2003 Jul 8;100(14):8164-9.
32. Ezech UI, Turek PJ, Reijo RA, Clark AT. Human embryonic stem cell genes OCT4, NANOG, STELLAR, and GDF3 are expressed in both seminoma and breast carcinoma. *Cancer*. 2005 Nov 15;104(10):2255-65.
33. Chen Y, Shi L, Zhang L, Li R, Liang J, Yu W, et al. The molecular mechanism governing the oncogenic potential of SOX2 in breast cancer. *J Biol Chem*. 2008 Jun 27;283(26):17969-78.
34. Hong H, Takahashi K, Ichisaka T, Aoi T, Kanagawa O, Nakagawa M, et al. Suppression of induced pluripotent stem cell generation by the p53-p21 pathway. *Nature*. 2009 Aug 27;460(7259):1132-5.
35. Marion RM, Strati K, Li H, Murga M, Blanco R, Ortega S, et al. A p53-mediated DNA damage response limits reprogramming to ensure iPS cell genomic integrity. *Nature*. 2009 Aug 27;460(7259):1149-53.
36. Hanna J, Saha K, Pando B, van Zon J, Lengner CJ, Creighton MP, et al. Direct cell reprogramming is a stochastic process amenable to acceleration. *Nature*. 2009 Dec 3;462(7273):595-601.
37. Heo I, Joo C, Kim YK, Ha M, Yoon MJ, Cho J, et al. TUT4 in concert with Lin28 suppresses microRNA biogenesis through pre-microRNA uridylation. *Cell*. 2009 Aug 21;138(4):696-708.
38. Qiu C, Ma Y, Wang J, Peng S, Huang Y. Lin28-mediated post-transcriptional

regulation of Oct4 expression in human embryonic stem cells. *Nucleic Acids Res.* 2010 Mar 1;38(4):1240-38.

39. Yu F, Yao H, Zhu P, Zhang X, Pan Q, Gong C, et al. let-7 regulates self renewal and tumorigenicity of breast cancer cells. *Cell.* 2007 Dec 14;131(6):1109-23.

40. Ivanova N, Dobrin R, Lu R, Kotenko I, Levorse J, DeCoste C, et al. Dissecting self-renewal in stem cells with RNA interference. *Nature.* 2006 Aug 3;442(7102):533-8.

41. Loh YH, Wu Q, Chew JL, Vega VB, Zhang W, Chen X, et al. The Oct4 and Nanog transcription network regulates pluripotency in mouse embryonic stem cells. *Nat Genet.* 2006 Mar 5;38(4):431-40.

42. van den Berg DL, Zhang W, Yates A, Engelen E, Takacs K, Bezstarosti K, et al. Estrogen-related receptor beta interacts with Oct4 to positively regulate Nanog gene expression. *Mol Cell Biol.* 2008 Oct;28(19):5986-95.

43. Feng B, Jiang J, Kraus P, Ng JH, Heng JC, Chan YS, et al. Reprogramming of fibroblasts into induced pluripotent stem cells with orphan nuclear receptor Esrrb. *Nat Cell Biol.* 2009 Feb;11(2):197-203.

44. Wu Q, Chen X, Zhang J, Loh YH, Low TY, Zhang W, et al. Sall4 interacts with Nanog and co-occupies Nanog genomic sites in embryonic stem cells. *J Biol Chem.* 2006 Jul 13.

45. Zhang J, Tam WL, Tong GQ, Wu Q, Chan HY, Soh BS, et al. Sall4 modulates embryonic stem cell pluripotency and early embryonic development by the transcriptional regulation of Pou5f1. *Nat Cell Biol.* 2006 Oct;8(10):1114-23.

46. Lim CY, Tam WL, Zhang J, Ang HS, Jia H, Lipovich L, et al. Sall4 regulates distinct transcription circuitries in different blastocyst-derived stem cell lineages. *Cell Stem Cell.* 2008 Nov 6;3(5):543-54.

47. Tsubooka N, Ichisaka T, Okita K, Takahashi K, Nakagawa M, Yamanaka S. Roles of Sall4 in the generation of pluripotent stem cells from blastocysts and fibroblasts. *Genes Cells.* 2009 Jun;14(6):683-94.

48. Kooistra SM, Thummer RP, Eggen BJ. Characterization of human UTF1, a chromatin-associated protein with repressor activity expressed in pluripotent cells. *Stem Cell Res.* 2009 Feb 12.

49. van den Boom V, Kooistra SM, Boesjes M, Geverts B, Houtsmuller AB, Monzen K, et al. UTF1 is a chromatin-associated protein involved in ES cell differentiation. *J Cell Biol.* 2007 Sep 10;178(6):913-24.

50. Zhao Y, Yin X, Qin H, Zhu F, Liu H, Yang W, et al. Two supporting factors greatly improve the efficiency of human iPSC generation. *Cell Stem Cell.* 2008 Nov 6;3(5):475-9.

51. Niwa H, Ogawa K, Shimosato D, Adachi K. A parallel circuit of LIF signalling

pathways maintains pluripotency of mouse ES cells. *Nature*. 2009 Jul 2;460(7251):118-22.

52. Han J, Yuan P, Yang H, Zhang J, Soh BS, Li P, et al. Tbx3 improves the germ-line competency of induced pluripotent stem cells. *Nature*. 2010 Feb 7.

53. Judson RL, Babiarz JE, Venere M, Bluelloch R. Embryonic stem cell-specific microRNAs promote induced pluripotency. *Nat Biotechnol*. 2009;27(5):459-61.

54. Samavarchi-Tehrani P, Golipour A, David L, Sung HK, Beyer TA, Datti A, et al. Functional genomics reveals a BMP-driven mesenchymal-to-epithelial transition in the initiation of somatic cell reprogramming. *Cell Stem Cell*. 2010 Jul 2;7(1):64-77.

55. Papapetrou EP, Tomishima MJ, Chambers SM, Mica Y, Reed E, Menon J, et al. Stoichiometric and temporal requirements of Oct4, Sox2, Klf4, and c-Myc expression for efficient human iPSC induction and differentiation. *Proc Natl Acad Sci U S A*. 2009 Jun 23.

56. Mitsui K, Tokuzawa Y, Itoh H, Segawa K, Murakami M, Takahashi K, et al. The Homeoprotein Nanog Is Required for Maintenance of Pluripotency in Mouse Epiblast and ES Cells. *Cell*. 2003 May 30;113(5):631-42.

57. Niwa H, Miyazaki J, Smith AG. Quantitative expression of Oct-3/4 defines differentiation, dedifferentiation or self-renewal of ES cells. *Nat Genet*. 2000;24(4):372-6.

58. Marson A, Foreman R, Chevalier B, Bilodeau S, Kahn M, Young RA, et al. Wnt signaling promotes reprogramming of somatic cells to pluripotency. *Cell Stem Cell*. 2008 Aug 7;3(2):132-5.

59. Lyssiotis CA, Foreman RK, Staerk J, Garcia M, Mathur D, Markoulaki S, et al. Reprogramming of murine fibroblasts to induced pluripotent stem cells with chemical complementation of Klf4. *Proc Natl Acad Sci U S A*. 2009 May 15.

60. Li R, Liang J, Ni S, Zhou T, Qing X, Li H, et al. A mesenchymal-to-epithelial transition initiates and is required for the nuclear reprogramming of mouse fibroblasts. *Cell Stem Cell*. 2010 Jul 2;7(1):51-63.

61. Ezashi T, Das P, Roberts RM. Low O₂ tensions and the prevention of differentiation of hES cells. *Proc Natl Acad Sci U S A*. 2005 Mar 29;102(13):4783-8.

62. Yoshida Y, Takahashi K, Okita K, Ichisaka T, Yamanaka S. Hypoxia enhances the generation of induced pluripotent stem cells. *Cell Stem Cell*. 2009 Sep 4;5(3):237-41.

63. Shi Y, Desponts C, Do JT, Hahm HS, Scholer HR, Ding S. Induction of pluripotent stem cells from mouse embryonic fibroblasts by Oct4 and Klf4 with small-molecule compounds. *Cell Stem Cell*. 2008 Nov 6;3(5):568-74.

64. Bhutani N, Brady JJ, Damian M, Sacco A, Corbel SY, Blau HM. Reprogramming towards pluripotency requires AID-dependent DNA demethylation. *Nature*. 2009 Dec 21.

65. Rai K, Huggins IJ, James SR, Karpf AR, Jones DA, Cairns BR. DNA demethylation in zebrafish involves the coupling of a deaminase, a glycosylase, and gadd45. *Cell*. 2008 Dec

26;135(7):1201-12.

66. Popp C, Dean W, Feng S, Cokus SJ, Andrews S, Pellegrini M, et al. Genome-wide erasure of DNA methylation in mouse primordial germ cells is affected by AID deficiency. *Nature*. 2010 Feb 25;463(7284):1101-5.
67. Doi A, Park IH, Wen B, Murakami P, Aryee MJ, Irizarry R, et al. Differential methylation of tissue- and cancer-specific CpG island shores distinguishes human induced pluripotent stem cells, embryonic stem cells and fibroblasts. *Nat Genet*. 2009 Dec;41(12):1350-3.
68. Deng J, Shoemaker R, Xie B, Gore A, LeProust EM, Antosiewicz-Bourget J, et al. Targeted bisulfite sequencing reveals changes in DNA methylation associated with nuclear reprogramming. *Nat Biotechnol*. 2009;27(4):353-60.
69. Huangfu D, Osafune K, Maehr R, Guo W, Eijkelenboom A, Chen S, et al. Induction of pluripotent stem cells from primary human fibroblasts with only Oct4 and Sox2. *Nat Biotechnol*. 2008 Oct 12;26(11):1269-75.
70. Huangfu D, Maehr R, Guo W, Eijkelenboom A, Snitow M, Chen AE, et al. Induction of pluripotent stem cells by defined factors is greatly improved by small-molecule compounds. *Nat Biotechnol*. 2008 Jul;26(7):795-7.
71. Kim K, Doi A, Wen B, Ng K, Zhao R, Cahan P, et al. Epigenetic memory in induced pluripotent stem cells. *Nature*. 2010 Jul 19.
72. Polo JM, Liu S, Figueroa ME, Kulalert W, Eminli S, Tan KY, et al. Cell type of origin influences the molecular and functional properties of mouse induced pluripotent stem cells. *Nat Biotechnol*. 2010 Jul 19.
73. Miura K, Okada Y, Aoi T, Okada A, Takahashi K, Okita K, et al. Variation in the safety of induced pluripotent stem cell lines. *Nat Biotechnol*. 2009 Jul 9.
74. Tsuji O, Miura K, Okada Y, Fujiyoshi K, Mukaino M, Nagoshi N, et al. Therapeutic potential of appropriately evaluated safe-induced pluripotent stem cells for spinal cord injury. *Proc Natl Acad Sci U S A*. 2010 Jul 13;107(28):12704-9.
75. Aasen T, Raya A, Barrero MJ, Garreta E, Consiglio A, Gonzalez F, et al. Efficient and rapid generation of induced pluripotent stem cells from human keratinocytes. *Nat Biotechnol*. 2008 Nov;26(11):1276-84.
76. Sun N, Panetta NJ, Gupta DM, Wilson KD, Lee A, Jia F, et al. Feeder-free derivation of induced pluripotent stem cells from adult human adipose stem cells. *Proc Natl Acad Sci U S A*. 2009 Sep 15;106(37):15720-5.
77. Miyoshi K, Tsuji D, Kudoh K, Satomura K, Muto T, Itoh K, et al. Generation of human induced pluripotent stem cells from oral mucosa. *J Biosci Bioeng*. 2010 Sep;110(3):345-50.

78. Tamaoki N, Takahashi K, Tanaka T, Ichisaka T, Aoki H, Takeda-Kawaguchi T, et al. Dental Pulp Cells for Induced Pluripotent Stem Cell Banking. *J Dent Res*. 2010 Aug;89(8):773-8.
79. Loh YH, Agarwal S, Park IH, Urbach A, Huo H, Heffner GC, et al. Generation of induced pluripotent stem cells from human blood. *Blood*. 2009;Advanced online publication(113):5476-9.
80. Giorgetti A, Montserrat N, Aasen T, Gonzalez F, Rodriguez-Piza I, Vassena R, et al. Generation of induced pluripotent stem cells from human cord blood using OCT4 and SOX2. *Cell Stem Cell*. 2009 Oct 2;5(4):353-7.
81. Osafune K, Caron L, Borowiak M, Martinez RJ, Fitz-Gerald CS, Sato Y, et al. Marked differences in differentiation propensity among human embryonic stem cell lines. *Nat Biotechnol*. 2008 Mar;26(3):313-5.
82. Newman AM, Cooper JB. Lab-Specific Gene Expression Signatures in Pluripotent Stem Cells. *Cell Stem Cell*. 2010 Aug 6;7(2):258-62.
83. Chin MH, Mason MJ, Xie W, Volinia S, Singer M, Peterson C, et al. Induced pluripotent stem cells and embryonic stem cells are distinguished by gene expression signatures. *Cell Stem Cell*. 2009 Jul 2;5(1):111-23.
84. Brons IG, Smithers LE, Trotter MW, Rugg-Gunn P, Sun B, Chuva de Sousa Lopes SM, et al. Derivation of pluripotent epiblast stem cells from mammalian embryos. *Nature*. 2007 Jul 12;448(7150):191-5.
85. Tesar PJ, Chenoweth JG, Brook FA, Davies TJ, Evans EP, Mack DL, et al. New cell lines from mouse epiblast share defining features with human embryonic stem cells. *Nature*. 2007 Jul 12;448(7150):196-9.
86. Hanna J, Cheng AW, Saha K, Kim J, Lengner CJ, Soldner F, et al. Human embryonic stem cells with biological and epigenetic characteristics similar to those of mouse ESCs. *Proc Natl Acad Sci U S A*. 2010 May 18;107(20):9222-7.
87. Araki R, Jincho Y, Hoki Y, Nakamura M, Tamura C, Ando S, et al. Conversion of Ancestral Fibroblasts to Induced Pluripotent Stem Cells. *Stem Cells*. 2009 Dec 17.
88. Chan EM, Ratanasirintraooot S, Park IH, Manos PD, Loh YH, Huo H, et al. Live cell imaging distinguishes bona fide human iPS cells from partially reprogrammed cells. *Nat Biotechnol*. 2009 Oct 11.

Table 1: iPS induction methods in human fibroblasts

Type of vector	Method	Genomic integration	factors d	Reprogramming efficiency in human fibroblasts e	Reference
Virus	Retrovirus	+	OSKM	++++	13
	Lentivirus	+	OSNL	+++	14
	Adenovirus	−a	OSKM	+	19
	Sendai virus	−b	OSKM	++++	20
DNA	Episomal plasmid	−a	OSKMNL T	+	24
	Transposon	−a, c	OSKM	++	21, 22
	Minicircle	−a	OSNL	+	23
RNA	RNA	−	OSKM	+++	25
Protein	Cell transparent protein	−	OSKM	+	26

a, absence of genomic integration should be experimentally examined.

b, absence of virus RNA genome should be experimentally examined.

c, Transposon vector is integrated into genome, but it can be removed.

d, O, OCT3/4; S, SOX2; K, KLF4; M, C-MYC; N, NANOG; L, LIN28; T, SV40-large T antigen.

e, +, <0.001%; ++, <0.01%; +++, <0.1%; +++, >0.1%

