

MINI REVIEW

Generation of pluripotent stem cells without the use of genetic material

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Induced pluripotent stem cells (iPSCs) provide a platform to obtain patient-specific cells for use as a cell source in regenerative medicine. Although iPSCs do not have the ethical concerns of embryonic stem cells, iPSCs have not been widely used in clinical applications, as they are generated by gene transduction. Recently, iPSCs have been generated without the use of genetic material. For example, protein-induced PSCs and chemically induced PSCs have been generated by the use of small and large (protein) molecules. Several epigenetic characteristics are important for cell differentiation; therefore, several small-molecule inhibitors of epigenetic-modifying enzymes, such as DNA methyltransferases, histone deacetylases, histone methyltransferases, and histone demethylases, are potential candidates for the reprogramming of somatic cells into iPSCs. In this review, we discuss what types of small chemical or large (protein) molecules could be used to replace the viral transduction of genes and/or genetic reprogramming to obtain human iPSCs.

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Pluripotent stem cells (PSCs) can be derived from terminally differentiated tissues by altering the epigenetic status of cells. These PSCs have the potential to differentiate into any cell type derived from the three germ layers.^{1–5} Cell type determination is heavily dependent on epigenetic process. The generation of iPSCs from differentiated cells is partly regulated by epigenetics. PSCs provide an unlimited cell source with the potential for use in studying diseases, drug screening, and regenerative medicine. Human PSCs provide a promising platform for obtaining patient-specific cells for various therapeutic and research applications. In general, induced pluripotent stem cells (iPSCs) are generated via genetic manipulation or by nuclear transfer to generate PSCs from somatic cells.⁶ However, nuclear transfer-generated PSCs raised ethical concerns and are technically difficult to prepare. The genetic manipulation of PSCs limits their clinical uses. Although embryonic stem cells (ESCs) do not need to be genetically manipulated, there are strong ethical concerns regarding human ESCs (hESCs), limiting their use in clinical applications.

iPSCs were first generated in 2006–2007 by the transduction of four transcription genes, Oct3/4, Sox2, c-Myc, and

Klf-4^{7–10} or Oct 4, Sox2, Nanog, and Lin28.¹¹ Following these studies, several researchers succeeded in generating iPSCs using fewer pluripotent genes. Of note, researchers generated iPSCs without transducing c-Myc, a potent oncogene.^{12–14} Currently, mouse iPSCs (miPSCs) can be generated by reprogramming a single gene, such as *Oct4*,^{15,16} or with the aid of small or large molecules in place of gene transduction.^{17–19} However, the low reprogramming efficiency of human iPSCs (hiPSCs) is a major drawback. The use of virus-mediated delivery of reprogramming factors, which leads to the permanent integration of oncogenes and potentially harmful genomic alterations,²⁰ is a serious concern. The use of genome-integrating viruses could cause insertional mutagenesis and unpredictable genetic dysfunction.^{9,21}

Therefore, several reprogramming technologies that do not use viral integration have been developed for iPSC production.^{22,23} These approaches include the use of non-integrating viruses,^{24–26} transposon-based systems,²⁷ and the delivery of reprogramming factors on plasmids.^{22,28–30} Adenovirus, lentivirus, Sendai virus, miRNA, and plasmid transfection methods have been reported to generate miPSCs^{28,31} and

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hiPSCs^{24,30,32–35} to minimize chromosomal disruption.¹⁸ Yu *et al.* generated hiPSCs by transfecting non-integrating episomal vectors.³⁰ In addition, the piggyBac transposon^{18,27,31} and Cre-recombinase excisable viruses³⁶ have been used to generate hiPSCs. The transgenes can be excised by inducible gene expression once reprogramming is established.^{25,27,36} However, there is evidence that there can be problems with residual DNA and chromosomal disruptions, resulting in harmful genetic alterations.¹⁸

The repeated transfection of modified mRNA encoding the reprogramming factors is also efficient for generating iPSCs.^{22,37} Although these strategies eliminate the threat of random viral integration into the host cell genome, these approaches are technically challenging and less efficient than viral transduction. Therefore, it is important to identify new conditions and small or large molecules that can promote reprogramming and ultimately replace all of the reprogramming transcription factors (TFs).^{14,38–41} For clinical applications, using small or large molecules to generate iPSCs are preferable to genetic manipulations. Recently, several novel methods have been reported for generation of iPSCs without the use of genetic material; these methods include protein-induced iPSCs (piPSCs) that are reprogrammed from somatic cells using cell-penetrating TF proteins,^{18,19} and chemically iPSCs (CiPSCs) that are reprogrammed from somatic cells using small molecules.^{14,17,20,38–49}

Human CiPSCs are a promising tool in the clinical application of iPSCs. CiPSCs can be reprogrammed to become iPSCs from somatic cells, without genetic manipulation, through the addition of small-molecule chemicals in the culture medium. In this review, we will discuss the generation of iPSCs without the use of genetic material and instead using small or large (protein) molecules. We will discuss types of small and/or large (protein) molecules that can replace specific viral transduction of pluripotent TFs to obtain piPSCs and CiPSCs from somatic cells.

PSCs REPROGRAMMING WITH PROTEINS (piPSCs)

In the reprogramming of somatic cells into iPSCs, one of the methods that avoids exogenous genetic introduction to the target cells is delivering the reprogramming proteins directly into cells rather than transducing the cells with TF genes. Previous researchers have reported that the proteins can be delivered into mammalian cells *in vitro* and *in vivo* by conjugating the proteins with a short peptide to guide their transduction, such as HIV transactivator of transcription (tat) or polyarginine.^{30,50–52} Various solubilization and refolding techniques have been developed so that recombinant proteins expressed in *E. coli* and contained in inclusion bodies can be re-folded into bioactive proteins. This allows for easy, large-scale production of therapeutic proteins.^{30,53} Currently, recombinant forms of Oct4, Sox2, Klf4, and c-Myc are commercially available. Table 1 summarizes the reprogramming of mouse and human somatic cells into piPSCs with the aid of proteins by transduction without TFs.

The challenge in delivering proteins into cells is the proteins' limited capacity to penetrate the cell membranes. Proteins that are capable of crossing the cell membrane barrier generally contain high proportions of basic amino acids, such as lysine and arginine.^{54,55} and the HIV tat protein has a short, basic segment of 48–60 amino-acid residues that is known to cross the cell membrane and to activate HIV-specific genes.^{18,54} In 2009, Zhou *et al.* attached a transfection domain of a polyarginine protein to the C terminus of the four reprogramming factors Oct4, Sox2, Klf4, and c-Myc to generate recombinant proteins that are able to permeate the plasma membranes of mouse embryonic fibroblasts (MEFs).¹⁹ The mouse piPSCs that were generated were stably expanded for 30 passages, and the morphology of the piPSCs was similar to ESCs, as they formed small, compact, domed colonies.¹⁹ The piPSCs expressed typical pluripotency markers, including ALP, SSEA1, Nanog, Oct4, and Sox2, as assayed by immunostaining. The expression of endogenous pluripotency genes was verified by RT-PCR. The piPSCs generated embryoid bodies in suspension and differentiated into cells characteristic of the three germ layers: (a) endoderm cells expressing AFP, FoxA2, GATA4, Sox17, albumin (hepatic marker), and Pdx1 (pancreatic marker); (b) mesoderm cells expressing Brachyury and mature beating cardiomyocytes expressing the CT3 and MHC markers; and (c) ectoderm cells expressing Pax5 and Sox1 (neural markers) and β III-tubulin and MAP2ab (mature neuronal markers).¹⁹ Although these findings are promising, the extremely low efficiency (0.006%) and poor reproducibility of the generation of piPSCs hinders its use as a general method for generating iPSCs.

The same year, Kim *et al.* reported the generation of piPSCs from human newborn fibroblasts (HNFs) using four recombinant cell-penetrating reprogramming proteins (Oct4, Sox2, Klf4, and c-Myc) fused with a cell-penetrating peptide (CPP, polyarginine with nine repeating arginine residues).¹⁸ The authors generated HEK293 cell lines that expressed each of the four human reprogramming proteins fused to CPP. HNFs were treated with cell extracts from the HEK293 cell lines. After repeated treatment with the cell extracts containing the reprogramming proteins, the HNFs ultimately became human piPSCs.¹⁸ The human piPSCs showed similar characteristics to hESCs (H9) in cell morphology and pluripotent marker expression and were cultured for more than 35 passages without loss of pluripotency, which suggests that the appropriate epigenetic reprogramming events occurred in these cells. The human piPSCs were successively differentiated into cells derived from the three germ layers both *in vitro* (embryonic formation) and *in vivo* (teratoma formation).¹⁸ Interestingly, Kim *et al.* could not generate mouse piPSCs when they applied the same method to mouse cells.¹⁸ This discrepancy might be due to a low concentration of reprogramming proteins, as they used whole-protein extracts from HEK293 cells as the source of the reprogramming proteins. Furthermore, Kim *et al.* did not add

Table 1 Reprogramming of mouse and human somatic cells into iPSCs with the aid of proteins by transduction without transcription factors (TFs)

TFs required	Somatic cells	PSCs	Small molecules	Efficiency (%)	Reference
<i>Mouse</i>					
No factor	MEFs (NIH3T3)	miMPCs	mESC (D3) extract with streptolysin O treatment	NA	60
No factor	MEFs	miPSCs	VPA, four recombinant proteins (OSKM) with polyarginine tag	0.006%	19
No factor	MEFs	miPSCs	VPA, three recombinant proteins (OSK) with polyarginine tag	0.002%	19
No factor	Mouse skin fibroblasts	miMPCs	Fish egg extract	NA	57
No factor	Mouse cardiac fibroblasts	miPSCs	mES (C57) cell line extract	0.001%	59
No factor	Mouse dermal fibroblasts	miPSCs	mES (C57) cell line extract	NA	56
<i>Human</i>					
No factor	Human new born fibroblasts	hiPSCs	HEK293 Cell extract containing Recombinant proteins with polyarginine tag	0.001%	18
No factor	Human NPCs derived from cord blood	hiPSCs	TSA, RG-108, reprogramming proteins (Oct4, Klf4, Sox2)	0.001%	90
No factor	Human newborn foreskin fibroblast BJ (CRL-2522)	hiPSCs (hiMPCs)	Fibromodulin	0.03%	58

small molecules to the culture medium,¹⁸ whereas Zhou *et al.* used valproic acid (VPA) for the reprogramming to generate mouse piPSCs.¹⁹ VPA is known to enhance the reprogramming efficiency of cells to generate miPSCs.⁴²

piPSC GENERATION USING CELL EXTRACTS

Jin *et al.* also generated mouse piPSCs using cell extracts instead of viral transduction. They found that cell extracts from only specific ESC lines could promote the reprogramming of mouse dermal fibroblasts into piPSCs.⁵⁶ Therefore, the authors performed protein microarrays to characterize the proteomes of different ESC lines that can and cannot reprogram the mouse dermal fibroblast. Protein extract from the ESC line that could promote reprogramming showed high levels of proteins that regulate protein synthesis and metabolism, compared with the other ESC lines that could not promote reprogramming into piPSCs; this result suggests that there are threshold concentrations of specific synthetic and metabolic proteins that the cells must exceed to initiate reprogramming.

Several researchers have reported that, in addition to ESC extracts, other cell extracts such as fish oocyte extracts⁵⁷ or a single extracellular matrix proteoglycan of fibromodulin⁵⁸ can promote the reprogramming of human fibroblast cells into human piPSCs or induced multipotent stem cells. In most cases, the specific proteins from the extracts that drive reprogramming are unknown.^{57,59,60} Furthermore, it has not yet been verified whether human piPSCs can be reprogrammed with high efficiency and high reproducibility from

somatic cells incubated with extracts of hESCs or other animal cells.

COMPARISON OF hiPSCs DERIVED FROM GENETIC MATERIAL AND PROTEINS

Rhee *et al.* compared multiple hiPSC lines derived from retrovirus-based, lentivirus-based, and protein-based reprogramming to hESCs based on their capacity to differentiate into neuronal stem cells (NSCs) and dopaminergic neurons.⁶¹ Optimized co-culturing and fine selection methods led to the efficient generation of NSCs and dopaminergic neurons from hESCs and all hiPSC lines tested, including piPSCs. NSCs and dopaminergic neurons derived from hiPSCs using lentiviral transduction showed residual expression of exogenous reprogramming genes, whereas hiPSCs derived from retroviral vectors and piPSCs did not express the exogenous reprogramming genes.⁶¹ In addition, the virus-based iPSCs exhibited early cellular senescence and limited expansion because of apoptosis during passaging, whereas hESCs and hiPSCs exhibited unlimited expansion without cellular senescence. NSCs derived from piPSCs were grafted into rats with striatal lesions, a model of Parkinson's disease. NSC engraftment resulted in striking behavioral recovery associated with a high proportion of TH⁺ (ie, dopamine-secreting) neurons, and the transplantation of NSCs rescued motor deficits. However, tumors formed when a large number of NSCs was grafted into the rats.⁶¹ The researchers also found that fully differentiated dopamine neurons are too vulnerable to survive transplantation; therefore, almost no functional recovery and no TH⁺

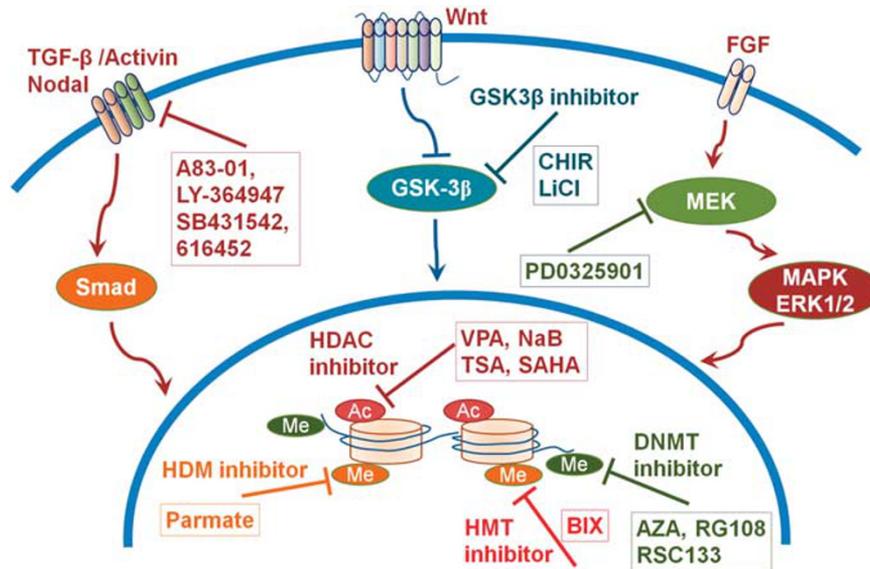


Figure 1 The signaling pathways underlying the chemical manipulation of stem cell fate and reprogramming. Epigenetic modulators can modify the chromatin structure to make it more permissive to changes in the epigenome during reprogramming. Small molecules that target signaling pathways can regulate the expression of pluripotent transcription factor genes, leading to the reprogramming of somatic cells into iPSCs. Several small-molecule inhibitors of epigenetic modification enzymes, such as DNA methyltransferases (DNMTs), histone deacetylases (HDAC), histone methyltransferases (HMT), and histone demethylases (HDM) that act as major players in forming the epigenetic landscape, have been selected as small chemical molecules for the reprogramming of somatic cells into iPSCs. The abbreviations of the small molecules are shown in Table 2.

neurons were generated in their study.⁶¹ This study elegantly described the superiority of hiPSCs generated by virus-free methods, although optimization is still required to remove residual undifferentiated cells and to avoid tumor generation. Such work will pave the way for standardized quality control before moving hiPSCs into clinical trials⁶² and will support the use of human piPSCs in clinical applications, such as personalized cell therapy for specific diseases.

The success of human piPSCs opens an avenue to generate safe production protocols for hiPSCs, as human piPSCs can eliminate the potential risks from the use of viral vectors and DNA transfection. However, the extremely low efficiency of piPSC generation (approximately 0.001%) is an issue blocking the use of human piPSCs in clinical applications.

SMALL MOLECULES THAT PROMOTE iPSC PRODUCTION INVOLVING FEW TFs

Small molecules that target specific signaling pathways and/or functions are valuable chemical tools in the reprogramming of somatic cells into iPSCs. These small molecules have the potential to play extensively important roles in both evaluating the basic biology of stem cells and promoting the development of clinical approaches toward regenerative medicine. Such approaches could open the door to cell replacement therapies, which use functional homogenous cells produced under chemically defined conditions *in vitro* and the development of small-molecule drugs to stimulate the endogenous patient cells to repair themselves and regenerate.²⁰ Here, we review recent progress made in using

small molecules to either sustain pluripotency or induce the reprogramming of somatic cells into iPSCs.

Previous studies have demonstrated that the expression of four TFs can reprogram several somatic cell types into iPSCs. Furthermore, iPSCs can be generated by viral integration of *Oct4/Sox2/Klf4* without expressing the oncogene *c-Myc*, which contributes to iPSC tumorigenicity, as determined by experiments that generated chimeras and their progeny mice.⁶³ For therapeutic usage, it is important to minimize the number of genes transduced into somatic cells to generate iPSCs.⁶⁴ However, decreasing the number of TFs leads to decreased iPSC generation efficiency. Therefore, several small molecules have been developed to enhance the generation efficiency of iPSCs.

Epigenetic changes are important for reprogramming somatic cells into iPSCs. Therefore, several small-molecule inhibitors against epigenetic-modifying enzymes that are major players in building the epigenetic landscape,⁴⁷ such as DNA methyltransferases (DNMTs), histone deacetylases (HDACs), histone methyltransferases (HMTs), and histone demethylases, were selected for somatic cell reprogramming into iPSCs. Epigenetic modulators can modify chromatin structure and make it more permissive to transcriptional machinery during somatic cell reprogramming. Some small molecules are summarized in Figure 1, which target transcription factors that are downstream in the signaling pathways. These small molecules can regulate gene expression level of pluripotent TFs, leading to somatic cell reprogramming into iPSCs, and it will be further discussed later in this review.

Small molecules with molecular weights less than 500–800 Da can freely permeate across the cell membrane and can be used to reprogram somatic cells into iPSCs.⁶⁵ It is systematically approached to identify small molecules to replace the reprogramming TFs or to promote reprogramming efficiency. One high-throughput method used to discover small molecules is as follows. Each well on the plate is seeded with somatic cells that are transduced with Oct4 promoter-driven enhanced green fluorescence protein and subsequently transcription factors, as endogenous *Oct4* expression is the first indication that iPSCs are being generated. Next, a panel of small molecules are screened, which can either replace Sox2, Oct4, and/or promote the efficiency of reprogramming. Colony numbers expressing GFP were evaluated as read out of this experiment. The colony generation efficiency is estimated from cells treated with and without small molecules.

Table 2 shows the small molecules that can replace TFs, which are required for reprogramming and increase reprogramming efficiency in generating iPSCs. These small molecules are inhibitors of epigenetic marks and signaling pathways.

SMALL MOLECULES THAT CAN REPLACE *Oct4*

Oct4 is the master regulatory pluripotency gene and may serve as a pluripotency determinant in reprogramming.^{15,66–68} BIX01294, a G9a HMTase inhibitor, was reported to induce miPSCs in place of *Oct4* (Table 2).⁶⁹ Furthermore, Forskolin (FSK, cAMP agonist), D4476 (casein kinase 1 inhibitor), and 2-methyl-5-hydroxytryptamine (5-HT3 agonist) can replace *Oct4* in mouse cells with the aid of other small molecules.¹⁷ RG108, a DNMT inhibitor, can replace *Oct4* during mouse skeletal muscle cell reprogramming into miPSCs where skeletal muscle cells endogenously express Sox2, *Klf4*, and *c-Myc*.⁷⁰ Figure 2 shows the chemical scheme of small molecules that may functionally replace *Oct4* and *Klf4* during somatic cell reprogramming into iPSCs.

The compounds 616452 (E-616452) and SB431542 are transforming growth factor (TGF)- β inhibitors that could replace Sox2 during mouse and human iPSC generation (Figure 1).^{15,69–71} Compound 616452 can replace Sox2 in the MEF reprogramming. However, 616452 does not actually act by inducing Sox2 expression in the target cells; rather, it enables reprogramming through the induction of *Nanog* transcription.⁶⁹ Another TGF- β inhibitor, LY-364947, can replace Sox2 in miPSC generation (Figure 1).^{69,72} Furthermore, the glycogen synthase kinase-3 (GSK-3) inhibitor CHIR99021 (CHIR), which activates the Wnt signaling pathway, was reported to induce the reprogramming of both mouse and human somatic cells without the use of a Sox2 transgene.⁷¹ The protein arginine methyltransferase inhibitor AMI-5 enables *Oct4*-induced reprogramming of MEFs in combination with the TGF- β inhibitor A83-01 (A-83-01) and can replace Sox2 during mouse somatic cell reprogramming.⁷³ BayK8644 (BayK), an L-channel calcium

agonist, was also reported to be able to replace Sox2 in combination with BIX01294 during MEF reprogramming into miPSCs.⁶³ Shh, purmorphamine, and oxysterol, the activator of Sonic hedgehog signaling, have been reported to upregulate *Bmi1*, Sox2, and *N-Myc* expression in mouse fibroblasts.⁷⁴ Therefore, these molecules can replace Sox2 in mouse fibroblast reprogramming into NSCs that are naturally expressing Sox2.⁷⁴

Staerk *et al.* applied a cell-based, high-throughput chemical screening method to identify small molecules that can replace Sox2 during mouse somatic cell reprogramming.⁷² From their *Nanog* reporter-based screening, they discovered that the Pan-Src family kinase inhibitors ipyrazine, dasatinib, and PP1 could replace Sox2 in MEF reprogramming into miPSCs.⁷² Figure 2 also shows the chemical scheme of small molecules that may functionally replace Sox2 during somatic cell reprogramming into iPSCs.

SMALL MOLECULES THAT CAN REPLACE *Klf4* and *c-Myc*

Kenpaullone has been reported as a substitute for *Klf4* in mouse cells, although the underlying mechanism is unknown.⁷⁵ Furthermore, several small molecules can increase the iPSC generation efficiency, indicating that the small molecules can replace *Klf4* and *c-Myc* during somatic cell reprogramming into iPSCs. For example, VPA (an HDAC inhibitor) improves reprogramming efficiency by more than 100-fold and enables efficient iPSC induction without the introduction of *c-Myc*.⁷⁶

SMALL MOLECULES THAT PROMOTE THE EFFICIENCY OF IPSC GENERATION

Figure 3 shows the chemical scheme of small molecules that promote somatic cell reprogramming into iPSCs. 5-Azacytidine, which is a DNMT inhibitor is reported to facilitate the transition of partially reprogrammed MEFs into fully reprogrammed iPSCs from 0.41% in partially reprogrammed MEFs to 77.8% with 5-azacytidine treatment after five passages.⁷⁷

The MEK inhibitor PD0325901 can inhibit the mitogen-activated protein kinase/extracellular signal-regulated kinase signaling pathway to promote late somatic cell reprogramming into mouse and human iPSCs (Figure 1).^{20,67,71} PD0325901 enhances the efficiency and completion of the iPSC reprogramming process. PD0325901 inhibits the growth of non-iPSC colonies and promotes the growth of reprogrammed iPSCs, leading to larger and more homogeneous iPSC colonies.⁶⁷

Tranylcypromine (brand name: Parnate), an H3K4 demethylation inhibitor, can also promote the reprogramming efficiency of mouse somatic cells into miPSCs (approximately 20-fold).¹⁵ Tranylcypromine is also known to activate endogenous *Oct4* expression in mouse embryonic carcinoma cells.⁷⁸

Sodium butyrate, a natural small fatty acid and HDAC inhibitor, increases the efficiency of mouse and human iPSC

Table 2 Small molecules facilitating somatic cell reprogramming and their function

<i>Small molecules</i>	<i>C^a</i>	<i>Host animal</i>	<i>Function</i>	<i>TFs to be replaced or function</i>	<i>Reference</i>
5-aza-CR, AZA	0.5 mM	Mouse	DMNT inhibitor	Promotion of reprogramming	77
RG108	0.04–500 μ M	Mouse	DMNT inhibitor	Sox2 (with BIX) or Oct4	63
RSC133	10 μ M	Human	DMNT inhibitor, Histone deacetylase inhibitor	Promotion of reprogramming	82
Sodium butyrate	0.5–1 mM	Mouse, human	HDAC inhibitor	Promotion of reprogramming	79
SAHA	5 μ M	Mouse	HDAC inhibitor	Promotion of reprogramming	42
TSA	20 nM	Mouse	HDAC inhibitor	Promotion of reprogramming	42
VPA	0.5–2 mM	Mouse, human	HDAC inhibitor	Promotion of reprogramming	15
Tranylcypromine (Parnate)	5–10 μ M	Mouse	H3K4 demethylation inhibitor (epigenetic modulator)	Promotion of reprogramming	71
BIX	0.5–2 μ M	Mouse	G9a HMTase inhibitor	Oct4	67
CHIR	3–10 μ M	Mouse, human	GSK-3 β inhibitor that activate Wnt signalling pathway	Sox2	15
Kenpaullone	5 μ M	Mouse	GSK-3/CDKs inhibitor	Klf4	75
Compound B6	1 μ M	Mouse	Akt-mediated inhibitor of GSK3- β	Promotion of reprogramming	84
LiCl	5–10 mM	Mouse and human	GSK-3 β inhibitor, LSD1 inhibitor	Promotion of reprogramming	70
616452 (E-616452, RepSox)	1 μ M	Mouse, human	TGF- β inhibitor (ALKinhibitor II)	Sox2	69
A83-01	0.5 μ M	Mouse, human	TGF- β inhibitor	Promotion of reprogramming	43
LY-364947	1 μ M	Mouse	TGF- β inhibitor	Sox2	72
SB431542	2 μ M	Mouse, human	TGF- β inhibitor	Promotion of reprogramming	71
PD0325901 (PD)	0.5–1 μ M	Mouse, human	MEK inhibitor	Promotion of reprogramming	67
AMI-5	5 μ M	Mouse	Protein arginine methyltransferase inhibitor	Sox2, Klf4 (with A-83-01)	73
N-oxaloylglycine	1 μ M	Human	Prolyl-4-hydroxylase inhibitor	Promotion of reprogramming	43
Compound B4 (TGFb-R1)	1 μ M	Mouse	ALK4 inhibitor	Promotion of reprogramming	84
Dasatinib	0.5 μ M	Mouse	Src family tyrosine kinase inhibitor	Sox2	72
iPY razine (iPY)	10 μ M	Mouse	Src family tyrosine kinase inhibitor	Sox2	72
PP1	10 μ M	Mouse	Src family tyrosine kinase inhibitor	Sox2	72
Rapamycin	0.3 nM	Mouse	mTOR inhibitor	Promotion of reprogramming	83
Compound B8	1–2 μ M	Mouse	IP3K inhibitor	Promotion of reprogramming	84
Compound B10	1–2 μ M	Mouse	P38 kinase inhibitor	Promotion of reprogramming	84
D4476	5 μ M	Mouse	CK1 inhibitor	Oct 4 with FSK and 2-Me-5HT	17
BayK	2 μ M	Mouse	a L-channel calcium agonist	Sox2	63
FSK	10–50 μ M	Mouse	cAMP agonist	Oct4 with 2-Me-5HT), and D4476	17
Prostaglandin E2	5 μ M	Mouse	cAMP agonist	Promotion of reprogramming	17
Rolipram	10 μ M	Mouse	cAMP agonist	Promotion of reprogramming	17
2-Me-5HT	5 μ M	Mouse	5-HT3 agonist	Oct4 with FSK and D4476	17
5-(4-Chloro-phenyl)-3-phenyl-pent-2-enoic acid (PS48)	5 μ M	human	PKD1 activator	Promotion of reprogramming	43
8-Br-cAMP	0.1–0.5 mM	Human	cAMP-dependent protein kinase activator	Promotion of reprogramming	65
Fructose 2,6-bisphosphate	10 mM	Human	Phosphofruktokinase 1 activator	Promotion of reprogramming	43
Quercetin	1 μ m	Human	Hypoxia-inducible factor pathway activator	Promotion of reprogramming	43

Table (Continued)

Small molecules	C ^a	Host animal	Function	TFs to be replaced or function	Reference
DZNep	0.05–0.1 μM	Mouse	Epigenetic modulators	Promotion of reprogramming	17
DNP	1 μM	Human	Oxidative phosphorylation uncoupler	Promotion of reprogramming	43
TTNPB	1 μM	Mouse	Retinoic acid receptor ligand	Promotion of reprogramming	17
Oxysterol	0.5–1 μM	Mouse	Sonic hedgehog signaling	Sox2, Klf4, and C-Myc	74
Purmorphamine	0.5–1 μM	Mouse	Sonic hedgehog signaling	Sox2, Klf4, and C-Myc	74
Shh	500 ng/ml	Mouse	Sonic hedgehog signaling	Sox2, Klf4, and C-Myc	74

Abbreviations: BayK, Bay K8644; BIX, BIX-01294; CHIR, CHIR99021; CK1, Casein kinase 1; DNMT, DNA methyltransferase; DNP, 2,4-dinitrophenol; DZNep, 3-deazaneplanocin; FSK, forskolin; HDAC, histone deacetylase; G9a HMTase, G9a histone methyltransferase; IP3K, inositol triphosphate 3-kinase; PDK1, 3'-phosphoinositide-dependent kinase 1; SAHA, suberoylanilide hydroxamic acid; TF, transcription factor; TSA, trichostatin A; VPA, valproic acid; 2-Me-5HT, 2-methyl-5-hydroxytryptamine; 5-aza-CR, AZA, 5-azacytidine; 8-Br-cAMP, 8-Bromoadenosine 3''5''-cyclic monophosphate.

^aC; Concentration used typical reprogramming experiments.

cell generation over a range of concentrations, such as 0.5–1 mM.^{79,80} The effect of sodium butyrate on reprogramming seems to be mediated by *c-Myc* and works during an early stage of reprogramming. In addition, sodium butyrate enhances the percentage of fully reprogrammed iPSCs by reducing the number of incomplete or partially reprogrammed cells.⁷⁹ Genome-wide gene expression analysis suggests that the upregulation of several pluripotent genes in sodium butyrate-treated MEFs during reprogramming is not through the suppression of the p53-p21 pathway, even though reprogramming efficiency is also known to be increased by the suppression of the p53-p21 pathway.⁸⁰

The anti-psychotic drug lithium chloride (LiCl) can accelerate the generation of mouse and human iPSCs.⁷⁰ The effect of LiCl on promoting reprogramming is partially dependent on its role as a GSK-3β inhibitor. However, LiCl also upregulates *Nanog*, which has not been observed after the treatment of somatic cells with other GSK-3β inhibitors. Furthermore, LiCl exerts its effects by promoting epigenetic modifications via the downregulation of LSD1, an H3K4-specific HDAC gene.⁷⁰

PS48, an activator of 3-phosphoinositide-dependent protein kinase 1, can also accelerate the reprogramming efficiency into hiPSCs.⁴⁰ PS48 activates the phosphatidylinositol 3-kinase/Akt pathway and significantly induces the expression of glycolytic genes, which results in the facilitation of metabolic reprogramming from the mitochondrial oxidation process used mainly by adult somatic cells into the glycolysis process used in PSCs.^{40,43} Owing to its lower oxidative stress, glycolytic metabolism is favorable over mitochondrial respiration in PSCs during cell proliferation and cell-cycle transition. The hypoxic condition and its effector gene, hypoxia-inducible factor 1α, which is extensively linked to promoting glycolytic metabolism, can also enhance the reprogramming efficiencies of both mouse and human cells.^{40,81}

Several other small molecules, such as A83-01 (TGF-β inhibitor),^{43,70} 3-deazaneplanocin (epigenetic modulator),¹⁷

2,4-dinitrophenol (DNP, oxidative phosphorylation uncoupler),⁴³ RSC133 (DNMT inhibitor),⁸² rapamycin (mTOR inhibitor),⁸³ compound B6 (AKT-mediated inhibitor of GSK3-β),⁸⁴ compound B8 (inositol triphosphate 3-kinase inhibitor),⁸⁴ compound B10 (P38 kinase inhibitor),⁸⁴ and vitamin C,⁷⁰ can facilitate the reprogramming efficiency of somatic cells into mouse and/or human iPSCs (Table 2).

SMALL MOLECULES CAN REPLACE SEVERAL TFS DURING MOUSE iPSC REPROGRAMMING

From the available knowledge of small molecules that can substitute for the essential TFs *Oct4*, *Sox2*, *Klf4*, and *c-Myc*, and promote reprogramming efficiency, several researchers tried to generate iPSCs by reducing the numbers of the TFs transduced into mammalian somatic cells. Figure 4 shows the schematic representation of some of the processes developed for miPSC generation from MEFs by reducing the numbers of TFs with and without small molecules. Table 3 summarizes the research for mouse somatic cell reprogramming into miPSCs by transduction with and without TFs and with the aid of small molecules.

NSCs and keratinocytes are known to endogenously express *Sox2*, *Klf4*, and/or *c-Myc* to some extent. Some examples of the gene expression levels of *Oct4*, *Sox2*, and *Nanog* in human fibroblasts, keratinocytes, CD133⁺ cells from cord blood, and NSCs are described in Figure 5.^{13,85,86} Several researchers tried to use endogenously expressing *Sox2*, *Klf4*, and/or *c-Myc* and to generate iPSCs with fewer numbers of pluripotent TFs. Kim *et al.* succeeded in preparing miPSCs from mouse NSCs using two exogenous TFs (*Oct4* and *Klf4* or *Oct4* and *c-Myc*).⁸⁷ They did not use small molecules to enhance reprogramming efficiency. Shi *et al.* also generated iPSCs from mouse NSCs using the G9a HMTase inhibitor BIX-01294 (BIX) in conjunction with the transduction of *Oct4* and *Klf4*, but without the use of oncogenic *c-Myc*.⁶⁷ BIX induced *Oct4* overexpression and facilitated the depression of *Oct4*, which promoted the iPSC reprogramming efficiency.^{20,67}

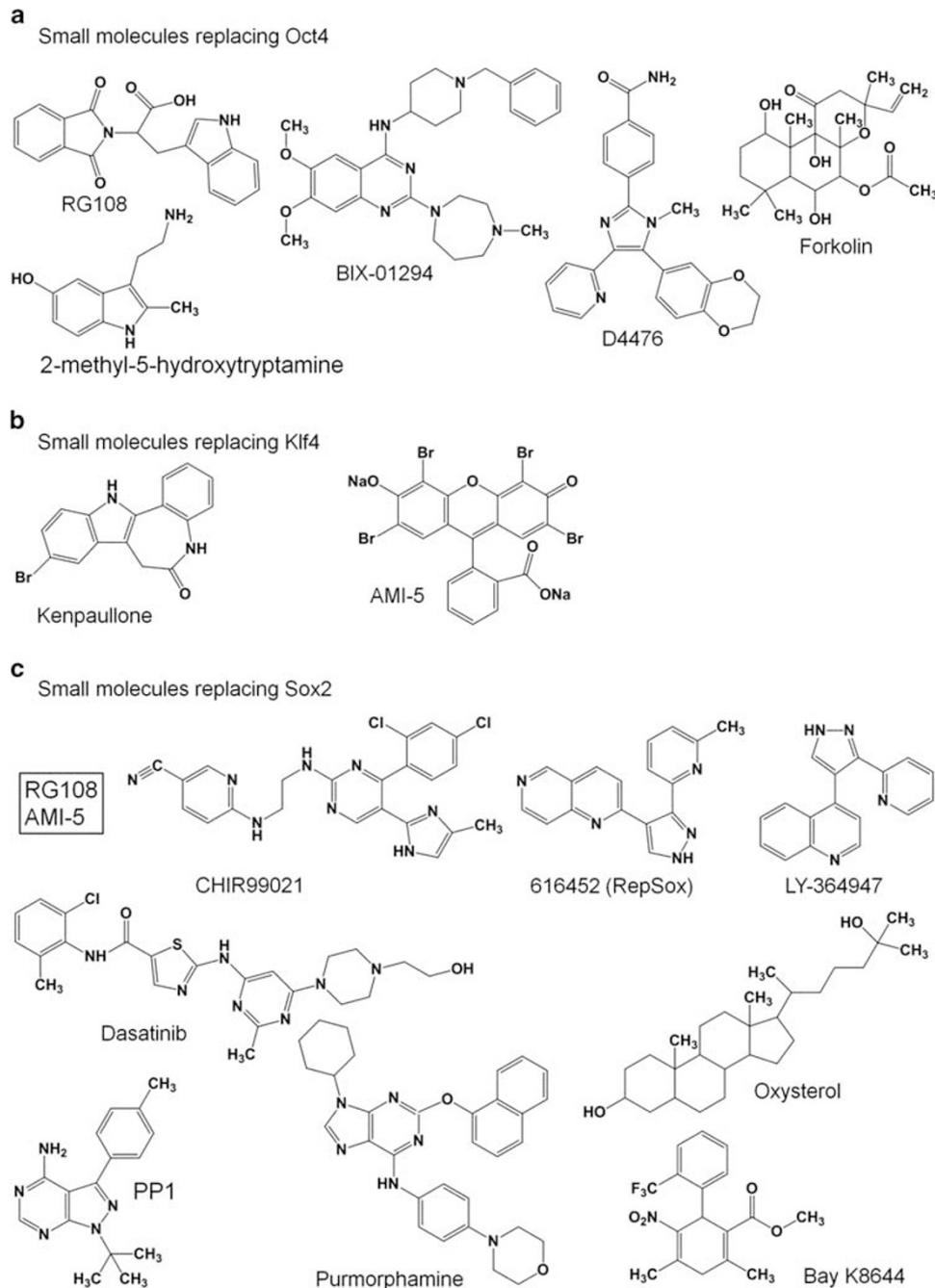


Figure 2 Representative schematic structures of small molecules that can replace *Oct4*, *Klf4*, and *Sox2* transduction in reprogramming to generate iPSCs. (a) Small molecules replacing *Oct4*; (b) small molecules replacing *Klf4*; (c) small molecules replacing *Sox2*.

Silva *et al.* also prepared miPSCs from mouse brain-derived NSCs using *Oct4* and *Klf4* transduction.⁸⁸ The cells rapidly adopted an undifferentiated morphology after a single round of transduction. However, these cells were partially reprogrammed and did not stably express endogenous *Oct4* or *Nanog*, and they were unable to colonize chimeras.⁸⁸ Therefore, the authors cultured the partially reprogrammed cells in medium containing a dual inhibitor of mitogen-activated

protein kinase signaling and GSK-3, 2i medium, along with leukemia inhibitory factor, which is a self-renewal cytokine for mouse PSCs.⁸⁸ The cells cultured in 2i medium with leukemia inhibitory factor induced the stable upregulation of *Oct4* and *Nanog*, transgene silencing, and competence for somatic and germline chimerism, which demonstrated that the cells were completely reprogrammed into miPSCs.⁸⁸ 2i medium is a powerful tool for generating miPSCs and

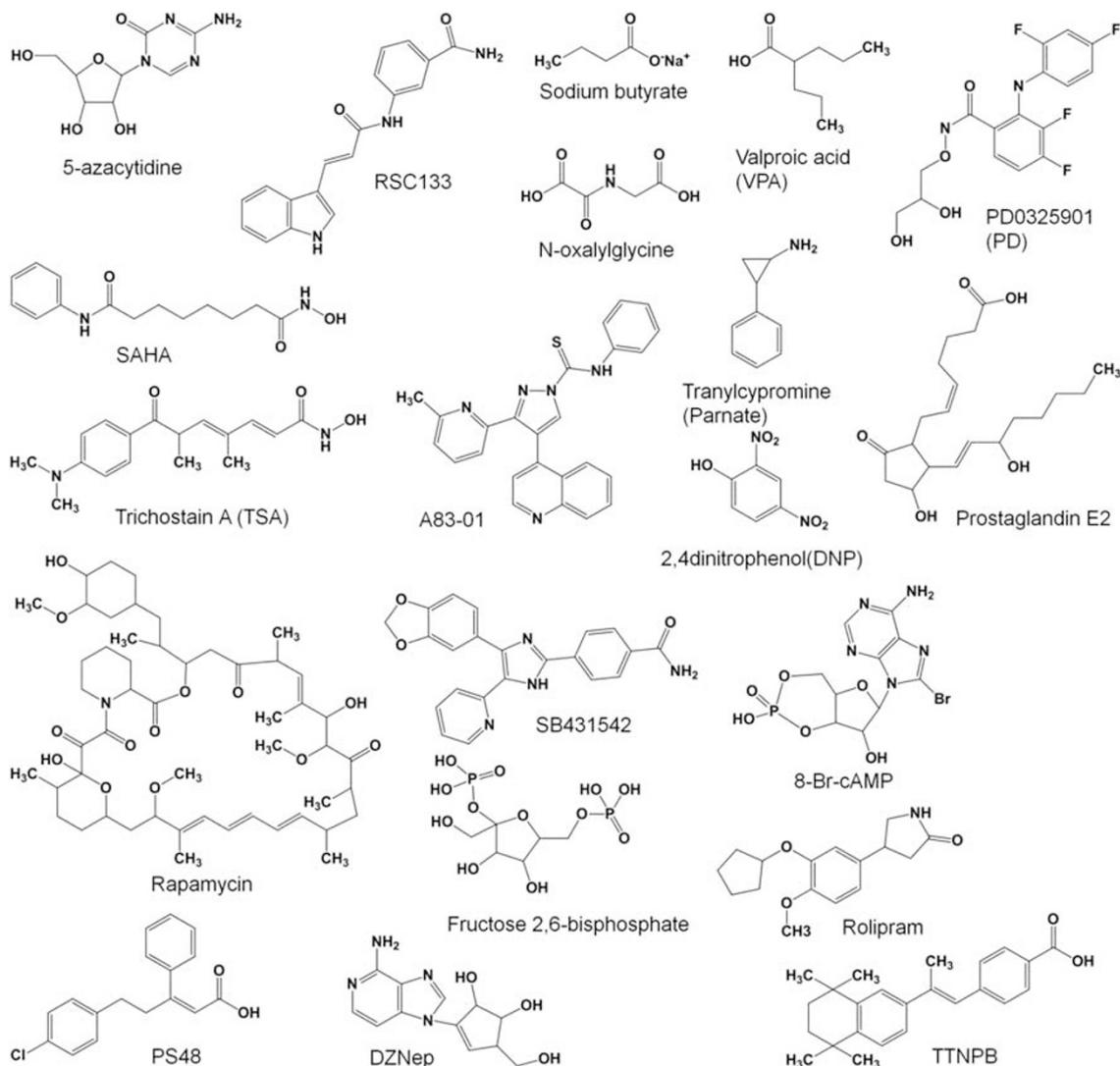


Figure 3 Representative schematic structures of small molecules that promote reprogramming to generate iPSCs.

seems to aid in the completion of mouse somatic cell reprogramming into miPSCs, although the effect of 2i medium on the generation of hiPSCs is currently unclear.

Other groups have also examined whether they could generate miPSCs from other somatic cells that do not endogenously express pluripotent TFs, such as MEFs, using small molecules and transducing fewer TFs. Huangfu *et al.* reprogrammed MEFs into miPSCs using VPA and transducing three factors without introducing the oncogene *c-Myc*. VPA, an HDAC inhibitor, improved the reprogramming efficiency by more than 100-fold under their conditions.⁴²

Shi *et al.* screened several drugs to identify small molecules that can generate iPSCs from MEFs transduced with *Oct4* and *Klf4* and thus compensate for the lack of *Sox2* over-expression.⁶³ They found that a combination of BIX and Bayk8644 (BayK), an L-channel calcium agonist, was effective at compensating for the lack of *Sox2* expression.⁶³ This

combination of small molecules (BIX and BayK) enabled the reprogramming of *Oct4/Klf4*-transduced MEFs, which do not endogenously express the TFs (ie, *Oct4*, *Sox2*, and *Klf4*) essential for reprogramming into iPSCs.^{7,8} RG108, a DNMT inhibitor, can act as a direct epigenetic modifier to shift epigenetic landscapes for cell reprogramming. In combination with BIX, RG108 can reprogram cells transduced with *Oct4* and *Klf4* into miPSCs with high efficiency.^{20,63}

VPA and CHIR99021 can improve the efficiency of miPSC colony generation after the transduction of three factors into MEFs, and *Sox2* can be replaced by the TGF- β inhibitor 616452.¹⁵ Therefore, Li *et al.* also generated miPSCs using only two TFs, *Oct4* and *Klf4*, in combination with VPA, CHIR99021, and 616452.¹⁵ The authors further discovered that miPSC colonies were generated using only one TF, *Oct4*, in combination with VC6 (VPA, CHIR99021, and 616452)

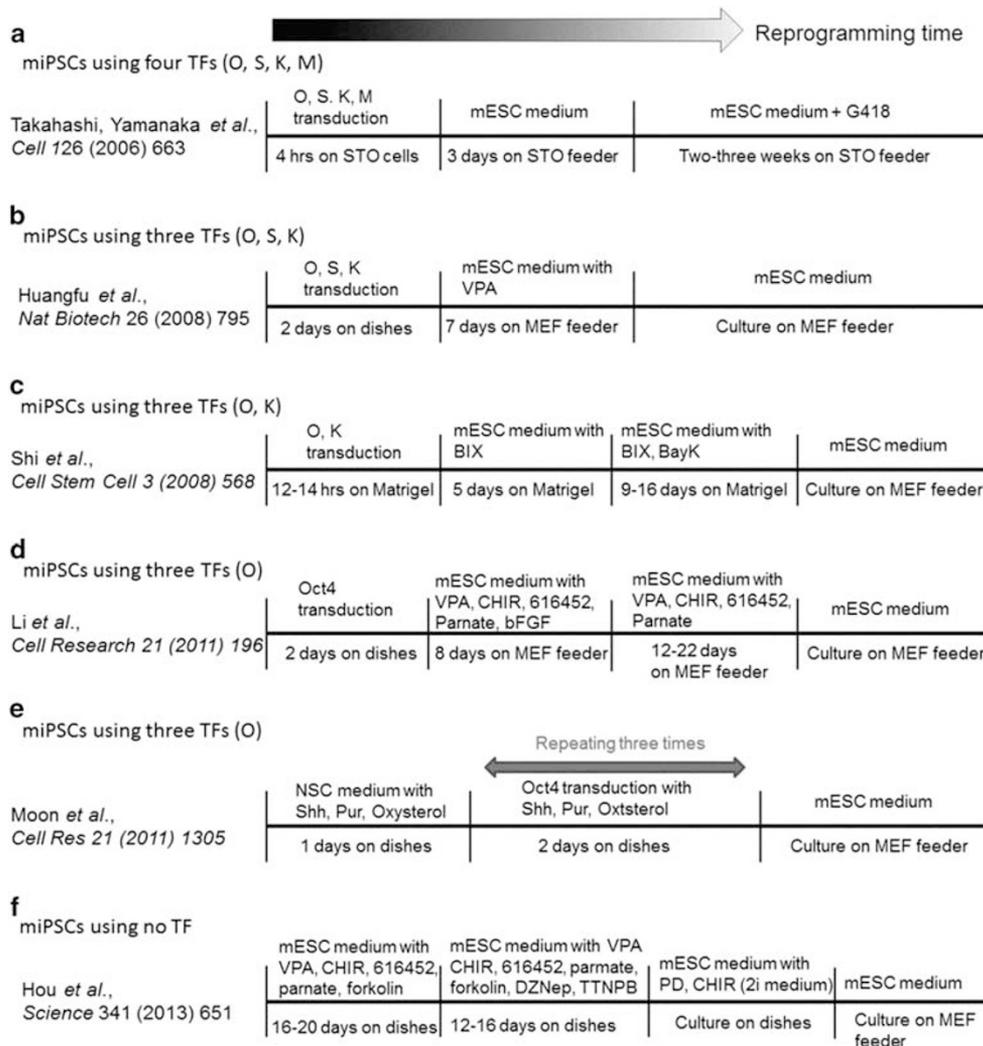


Figure 4 Schematic representation of the process of miPSC generation from MEFs by reducing the number of TFs with and without small molecules. (a) miPSCs using four TFs (Oct4 [O], Sox2 [S], Klf4 [K], and c-Myc [M]);⁷ (b) miPSCs using three TFs (O, S, K);⁴² (c) miPSCs using two TFs (O, K);⁶³ (d, e) miPSCs using one TF (O);^{15,74} and (f) miPSCs using no TFs.¹⁷

treatment when MEFs and adult mouse fibroblasts were cultured for 30 days. However, the efficiency was only 0.0005% (one colony in 2×10^5 cells).¹⁵ They confirmed that miPSCs could not be generated in the absence of VPA, CHIR 99021, or 616452 in their experiments.¹⁵ Because tranylcypromine significantly promoted miPSC generation by approximately 20-fold, Li *et al.* succeeded in generating miPSCs by transduction of *Oct4* alone with the addition of VPA, CHIR99021, 616452, and tranylcypromine (VC6T) in the culture medium.¹⁵ It is thought that the small-molecule combination including VC6T facilitated miPSC generation by lowering several major barriers to the reprogramming process. VPA (an HDAC inhibitor) and tranylcypromine (an H3K4 demethylation inhibitor) are epigenetic modulators that have been reported to facilitate iPSC generation.^{42,89} From the effects of VPA and tranylcypromine, H3K4 demethylation and HDAC may be two major epigenetic

barriers in the generation of miPSCs, suppressing the pluripotency transcriptional network. GSK3- β inhibition by CHIR99021 or TGF- β signaling inhibition by 616452 could efficiently replace *Sox2* for reprogramming.¹⁵ GSK3- β and TGF- β signaling should also be another two critical barriers that suppress the reprogramming process. Therefore, overcoming these four major reprogramming barriers, ie, two epigenetic barriers and two signaling barriers, may allow researchers to generate miPSCs by *Oct4* induction alone.¹⁵

miPSC GENERATION USING ONE TF

Yuan *et al.* generated miPSCs from MEFs using only one factor, *Oct4*. They treated MEFs with a combination of small molecules, including AMI-5, a protein arginine methyltransferase inhibitor, and A83-01, a TGF- β inhibitor, to generate miPSCs.⁷³ miPSCs were able to generate live-born pups through tetraploid complementation assays, indicating

Table 3 Reprogramming of mouse somatic cells into miPSCs by transduction with and without transcription factors (TFs) with the aid of small molecules

TFs required ^a	Somatic cells	PSCs	Small molecules	Efficiency (%)	Reference
<i>Four factors</i>					
OSKM	MEFs	miPSCs	None	0.02%	7
OSKM	Mouse hepatocyte and gastric epithelial cells	miPSCs	None	0.01%	10
OSKM	Mouse liver and stomach cells	miPSCs	None	0.01%	10
OSKM	MEFs	miPSCs	Compound B6, B8, and/or B10	0.14–0.35%	84
<i>Three factors</i>					
KSM	Mouse NPCs	miPSCs	None	0%	67
KSM	Mouse NPCs	miPSCs	BIX	0.004%	67
OSK	MEFs	miPSCs	None	0.001–0.0026%	12
OSK	MEFs	miPSCs	VPA	0.089%	42
OSK	MEFs	miPSCs	CHIR	0.18%	71
<i>Two factors</i>					
OK	Mouse NPCs	miPSCs	None	0.004–0.006%	87
OK	Mouse NPCs	miPSCs	BIX	0.034%	67
OK	Mouse NPCs	miPSCs	PD + CHIR (2i)	0.0125%	88
OK	MEFs	miPSCs	None	0.003%	69
OK	MEFs	miPSCs	BIX/BayK	0.022%	63
OK	MEFs	miPSCs	CHIR	0.006%	71
OK	MEFs	miPSCs	616452	0.05%	69
OK	MEFs	miPSCs	VPA, CHIR, 616452	0.01–0.04%	15
<i>One factor</i>					
O	Mouse NPCs	miPSCs	None	0.004%	16
O	MEFs	miPSCs	None	0%	15
O	MEFs	miPSCs	VPA, CHIR, 616452, Parnate	0.05–0.08%	15
O	MEFs	miPSCs	AMI-5, A-83-01	0.02%	73
O	MEFs	miPSCs	Shh, purmorphamine, or oxysterol	0.11%	74
<i>No factor</i>					
No factor	Mouse skeletal myoblasts	miPSCs	RG108	0.11%	68
No factor	MEFs	miPSCs	VPA, CHIR, 616452, Parnate, Forkolin, DZNep	0.04%	17
No factor	MEFs	miPSCs	VPA, CHIR, 616452, Parnate, Forkolin, DZNep, TTNPB	0.2%	17

^aO, S, K, and M indicate Oct4, Sox2, Klf-4, and c-Myc, respectively.

that the miPSCs achieved full reprogramming. Their study suggests that the regulation of protein arginine methylation by inhibition with A83-01 is also involved in the reprogramming process into miPSCs.⁷³ The efficiency of miPSC generation was reported to be 0.02% in their study.⁷³

Moon *et al.* also generated miPSCs from mouse fibroblasts using only one factor, *Oct4*, with the aid of the small molecules of Shh, purmorphamine, and oxysterol.⁷⁴ These small molecules can activate sonic hedgehog signaling, which compensates for *Bmi1* gene expression. *Bmi1* expression in

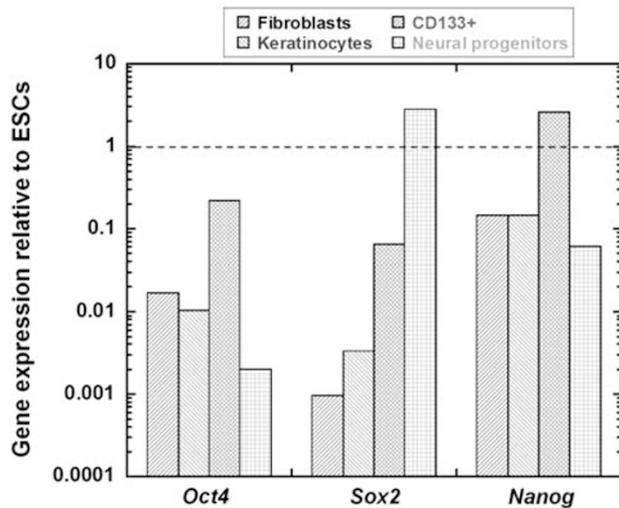


Figure 5 Relative gene expression levels of Oct4, Sox2, and Nanog in human fibroblasts, keratinocytes, CD133⁺ cells from cord blood, and NSCs. The relative gene expression levels in fibroblasts, keratinocytes, and CD133⁺ cells compared with hESCs were calculated from the data reported by Giorgetti *et al.*⁸⁵ and Page *et al.*⁸⁶ The relative gene expression levels in human NSCs compared with hESCs were used from the data reported by Kim *et al.*¹³

mouse fibroblasts leads to transdifferentiation of mouse fibroblasts into NSC-like cells, which can be subsequently reprogrammed into miPSCs by the transduction of *Oct4*.⁷⁴ The efficiency of miPSC generation was found to be 0.11% in their study.⁷⁴

MOUSE CiPSC GENERATION USING SMALL-MOLECULE COCKTAILS

Hou *et al.* prepared miPSCs solely using a combination of seven small-molecule compounds that are chemically defined without using transduction or transfection of TFs.¹⁷ It is difficult to select adequate small molecules that can replace the master regulatory gene *Oct4*. Therefore, Hou *et al.* first searched for small molecules that enabled MEF reprogramming in the absence of *Oct4* using MEFs expressing *Oct4* promoter-driven GFP to identify small molecules that facilitate cell reprogramming.¹⁷ They identified FSK, 2-methyl-5-hydroxytryptamine, and D4476 as chemical substitutes for *Oct4* after screening up to 10 000 small molecules, and they chose to use FSK as the chemical substitute of *Oct4* in their research.¹⁷ Because they had already developed the protocol to generate miPSCs using a small-molecule cocktail, ‘VC6T’ (VPA, CHIR99021, 616452, and tranilcypromine), with a single-gene transduction of *Oct4*,¹⁵ they developed mouse CiPSCs using small-molecule cocktails in the absence of the transduction or transfection of small molecules. They used a four-step protocol to generate mouse CiPSCs (Figure 4f). (a) MEFs were first cultured with mESC medium containing VPA, CHIR99021, 616452, tranilcypromine, and FSK (VC6FT) for 16–20 days. (b) The

cells were then cultured with mESC medium containing VC6FT, 3-deazaneplanocin (DZNep, epigenetic modulator), and TTNPB (a synthetic retinoic acid receptor ligand). In these cells, the expression levels of most of the pluripotency marker genes were elevated but appeared to still be lower than those found in mESCs, which indicated a partially reprogrammed cell state. (c) In the third stage, the cells were cultured in mESC medium containing PD0325901 and CHIR99021 (2i medium), which promotes complete cellular reprogramming. (d) The colonies exhibiting mESC-like morphologies were shifted onto MEFs and cultured in mESC medium.¹⁷ The reprogramming efficiency was as high as 0.2%.¹⁷ CiPSCs prepared in this research resembled mESCs in terms of their gene expression profiles, epigenetic status, and potential for differentiation and germline transmission. This research suggests that exogenous ‘master genes’ are dispensable for generating miPSCs using small molecules. This chemical reprogramming strategy opens the door to generate functional, desirable cell types for clinical applications, provided we can succeed in generating human CiPSCs in the future.

SMALL MOLECULES CAN INDUCE HUMAN iPSCs IN COMBINATION WITH A FEW TFs

Small molecules successively promote the generation of miPSCs by reducing the numbers of TFs required, as shown in the previous section. Researchers started to investigate the generation of hiPSCs by reducing the numbers of TFs with the aid of small molecules. Figure 6 illustrates some schematic representations of the process of hiPSC generation from human somatic cells. Table 4 summarizes reported studies for human somatic cell reprogramming into hiPSCs by transduction with and without TFs in combination with small molecules. Only a few small molecules have been reported to promote reprogramming and/or to replace TFs during hiPSC generation compared with miPSC generation. These molecules for hiPSC generation include sodium butyrate (HDAC inhibitor), VPA (HDAC inhibitor), CHIR99021 (GSK3- β inhibitor), LiCl (GSK3- β inhibitor), 616452 (TGF- β inhibitor), SB431542 (TGF- β inhibitor), PD325901 (MEK inhibitor), N-oxaloylglycine (prolyl-4-hydroxylase inhibitor), PS48 (3-phosphoinositide-dependent protein kinase 1 activator), 8-Br-cAMP (cAMP-dependent protein kinase activator), fructose 2,6-bisphosphate (phosphofructokinase 1 activator), quercetin (hypoxia-inducible factor pathway activator), and 2,4-dinitrophenol (oxidative phosphorylation uncoupler; Table 2). It will be important to evaluate whether other small molecules that have biological activities in miPSC reprogramming are valid for use in hiPSC reprogramming.

Currently, the minimum transduction of *Oct4* in combination with chemically defined small molecules is necessary to generate hiPSCs. This requirement is because the efficiency of hiPSC generation is much less than that of miPSC generation (eg, 0.0005–0.01%).

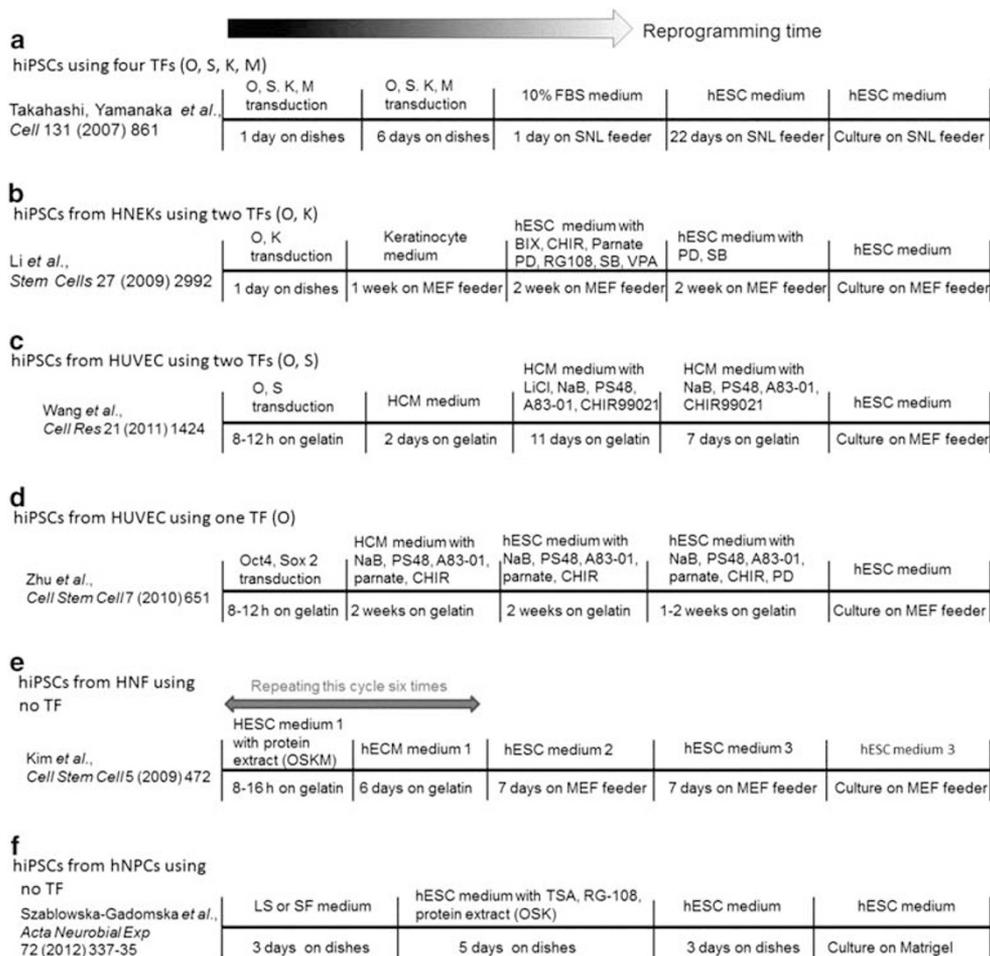


Figure 6 Schematic representation of hiPSC generation from human somatic cells by reducing the number of TFs with and without small molecules. (a) hiPSCs using four TFs (Oct4 [O], Sox2 [S], Klf4 [K], and c-Myc [M]);⁸ (b) hiPSCs from human neonatal epidermal keratinocytes (HNEKs) using two TFs (O, K);⁷¹ (c) hiPSCs from human umbilical vein endothelial cells (HUVECs) using two TFs (O, S);⁷⁰ (d) hiPSCs from HUVECs using one TF (O);⁴³ (e) hiPSCs from human newborn fibroblasts (HNFs) using no TFs;¹⁸ and (f) hiPSCs from human NSCs using no TFs.⁹⁰ HCM medium indicates EndoGRO-VEGF complete medium (CHEMICON). LS and SF medium indicates low-serum and serum-free media, respectively. O, S, K, and M indicate the TFs Oct4, Sox2, Klf4, and c-Myc, respectively.

NSCs endogenously express *Sox2*, *Klf4*, and/or *c-Myc* to some extent, as was discussed in the previous section (Figure 5). Therefore, Kim *et al.* reprogrammed human fetal NSCs into hiPSCs by the transduction of only *Oct4*.¹³ Their work suggests that only one TF, *OCT4*, should be sufficient to reprogram human fetal NSCs into hiPSCs. However, it is very difficult to obtain human fetal NSCs to generate patient-specific hiPSCs, and the efficiency of hiPSC generation is reported to be only 0.006% in their study.¹³

Zhu *et al.* developed their four-step protocol to generate hiPSCs from neonatal human epidermal keratinocytes, human umbilical vein endothelial cells (HUVECs), and amniotic-derived cells.⁴³ In the case of HUVEC-derived hiPSCs, the following protocol was used. (a) In the first stage, *Oct4* was transduced into cells cultured on gelatin-coated dishes for 8–12 h. (b) In the second stage, the cells were

cultured in HUVEC medium containing sodium butyrate, PS48, A83-01, tranylcypromine, and CHIR99021 for 2 weeks on the gelatin. (c) In the third stage, the cells were cultured in hESC medium containing sodium butyrate, PS48, A83-01, tranylcypromine, and CHIR99021 for another 2 weeks on the gelatin. (d) In the fourth stage, the cells were cultured in hESC medium containing sodium butyrate, PS48, A83-01, tranylcypromine, CHIR99021, and PD0325901 for an additional 1–2 weeks on the gelatin to complete the full cellular reprogramming (Figure 6d). It was suggested that the single TF, *Oct4*, combined with a defined small-molecule cocktail is capable of reprogramming several human somatic cell types into hiPSCs that are functionally similar to pluripotent hESCs in terms of morphology, gene and protein expression, and differentiation capacity.⁴³ However, the reprogramming efficiency was extremely low (0.004%) because hiPSCs rather than miPSCs were generated.

Table 4 Reprogramming of human somatic cells into hiPSCs by transduction with and without TFs with the aid of small molecules

TFs required ^a	Somatic cells	PSCs	Small molecules	Efficiency (%)	Reference
<i>Four factors</i>					
OSKM	Human dermal fibroblasts	hiPSCs	None	0.02%	8
OSKM	hFFs	hiPSCs	RSC133	3 Times higher than control	82
<i>Two factors</i>					
OK	Human fetal NPCs	hiPSCs	None	0.006%	13
OS	Human cord blood-derived stem cells	hiPSCs	None	0.006%	64
OK	Human neonatal keratinocyte	hiPSCs	CHIR99021, Parnate (and PD0325901, SB431542)	0.005–0.01%	71
OK	Human neonatal epidermal keratinocytes	hiPSCs	A-83-01, PD032590, NaB, PS48 (+ Parnate, CHIR99021)	0.025%	43
OS	HUVEC	hiPSCs	A83, NaB, PS48, CHIR88021, LiCl	0.0015%	70
<i>One factor</i>					
O	Human fetal NPCs	hiPSCs	None	0.004%	13
O	Human neonatal epidermal keratinocytes	hiPSCs	A-83-01, PD032590, sodium butyrate, PS48 (+ Parnate, CHIR99021)	0.004%	43
O	HUVECs and amniotic fluid-derived cells	hiPSCs	A83-01, PD032590, NaB, PS48 (+ Parnate, CHIR99021)	0.0025–0.01%	43
O	HUVEC	hiPSCs	A83-01, NaB, PS48, LiCl, CHIR99021 (or PD0325901)	0.0005%	70

Abbreviations: hFF, human foreskin fibroblast; TF, transcription factor.
^aO, S, K, and M indicate Oct4, Sox2, Klf-4, and c-Myc, respectively.

Wang *et al.* also generated hiPSCs using either one transduced factor (*Oct4*) or two transduced factors (*Oct4* and *Sox2*) with the aid of small molecules.⁷⁰ They used small-molecule cocktails similar to those used by Zhu *et al.*⁴³ but also treated the cells with LiCl (5 mM) from days 3 to 18, which facilitated miPSC and hiPSC generation (Figure 6c).⁷⁰ hiPSC colonies were picked for expansion on feeder cells after approximately 1 month. The effect of LiCl on promoting reprogramming was only partially dependent on its major target, GSK-3 β .⁷⁰ However, LiCl is unlike other GSK-3 β inhibitors, as it enhances *Nanog* expression and also promotes its transcriptional activity. LiCl also works by promoting epigenetic modifications via the downregulation of an H3K4-specific histone demethylase, LSD1. However, the efficiency of hiPSC generation was still extremely low (0.0015 and 0.0005% for two-factor and one-factor transduction, respectively).

If hiPSCs can be generated from patient-specific cells and/or different human leukocyte antigen (HLA) types of human somatic cells using only chemically defined small molecules

with high efficiency (eg, preferentially >0.1%), the door would be opened for the potential use of hiPSCs in clinical applications. Currently, to our knowledge, hiPSC generation solely based on chemically defined small molecules has not yet been reported, although hiPSCs have been generated using cell extracts and/or proteins without the use of TFs.^{18,58,90}

CONCLUSIONS AND PERSPECTIVES

Introduction of small and large molecules can target signaling transduction pathways and can affect DNA replication, cell differentiation, apoptosis, and the reprogramming of the cells into iPSCs. Several specific small molecules can successfully enhance the reprogramming efficiencies of mouse and human somatic cells into iPSCs. Since 2013, miPSCs have been generated via treatment with small molecules without the use of genetic material.^{17,68} However, it is still challenging to generate hiPSCs by treating cells with only small molecules. The generation of human and mouse piPSCs using pluripotent proteins or cell extracts without the

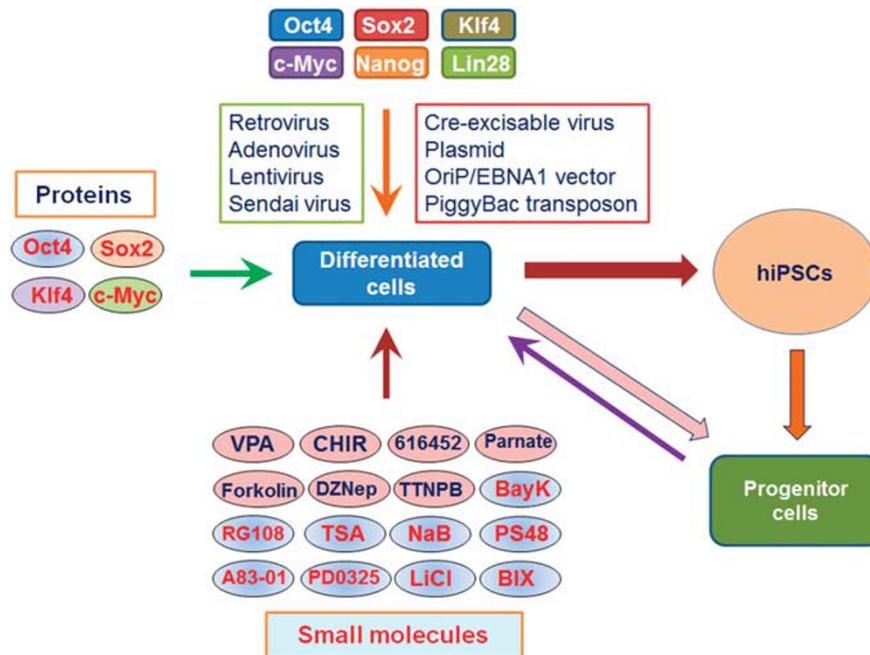


Figure 7 Schematic illustration of somatic cell reprogramming to iPSCs and progenitor or adult stem cells. Somatic cells can be reprogrammed to iPSCs using viral or non-viral introduction of exogenous TFs or protein transfection. Small molecules can either substitute for certain TFs and/or improve reprogramming efficiency by epigenetic modifications or signaling pathway regulation. The abbreviations of the small molecules are shown in Table 2.

use of genetic material has been reported.^{18,21} However, currently, piPSCs are not a popular method for generating iPSCs, although more than 5 years has passed since the first reports of their generation. The hesitancy to adopt the method is likely due to the extremely low generation efficiency and the difficulty of preparing pluripotent proteins tagged with CPP. Figure 7 summarizes the reprogramming methods that have been developed and that may be promising in the future. Currently, target cells, such as dopamine-secreting cells, insulin-secreting β cells, and cardiomyocytes, may be prepared from PSCs as follows: (a) somatic cells from blood, fat tissue, or other sources of tissues are isolated; (b) the somatic cells are reprogrammed into iPSCs; and (c) iPSCs are differentiated into the targeted cells. In this case, which includes the use of hESCs and hiPSCs, it is extremely difficult to obtain highly pure populations of the target cells. Furthermore, it is impossible to avoid the potential for tumor generation when these targeted cells are transplanted into humans.⁹¹ Therefore, we suggest that the direct reprogramming of somatic cells into progenitor (stem) cells, including adult stem cells, such as NSCs, cardiomyocyte progenitor cells, hepatocyte stem cells, hematopoietic stem cells, and mesenchymal stem cells, as an attractive alternative for clinical applications. It will be interesting to develop small molecules to guide human somatic cells into the transdifferentiation of tissue-specific progenitor cells or stem cells.^{76,92–95} In this case, xeno-free cultures are much easier for culturing the progenitor cells compared with PSCs because MEFs are not required for the culturing of progenitor cells and adult stem cells. Although

NSCs are reported to be able to proliferate for more than 20–130 passages,^{96–98} mesenchymal stem cells, such as adipose-derived stem cells and amniotic fluid stem cells, have limited proliferation capacities (eg, 8–12 passages). Therefore, the establishment of small molecules to extend the proliferation of adult stem cells and progenitor cells should be a priority in regenerative medicine. Because bone marrow stem cells and hematopoietic stem cells are ready to be used in clinical applications, the only obstacle to the use of these adult stem cells in clinical applications is their limited proliferation and their overall shortage, which leads to low numbers of clinical trials. The shortages of progenitor cells and adult stem cells can be addressed by reprogramming somatic cells into progenitor cells and adult stem cells using small molecules, which do not disrupt or interrupt host cell genomes. The development of small molecules to guide human somatic cells into progenitor cells, adult stem cells, and iPSCs will open avenues for the clinical application of these types of progenitor cells and stem cells.^{65,99,100}

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DISCLOSURE/CONFLICT OF INTEREST

The authors declare no conflict of interest.

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