

Generation of Human Induced Pluripotent Stem Cells by Direct Delivery of Reprogramming Proteins

Dohoon Kim,^{1,5} Chun-Hyung Kim,^{1,5} Jung-Il Moon,¹ Young-Gie Chung,³ Mi-Yoon Chang,¹ Baek-Soo Han,¹ Sanghyeok Ko,¹ Eungi Yang,¹ Kwang Yul Cha,⁴ Robert Lanza,^{3,*} and Kwang-Soo Kim^{1,2,4,*}

¹Molecular Neurobiology Laboratory, Department of Psychiatry and McLean Hospital, Harvard Medical School

²Harvard Stem Cell Institute

115 Mill Street, Belmont, MA 02478, USA

³Stem Cell and Regenerative Medicine International, 381 Plantation Street, Worcester, MA 01605, USA

⁴CHA Stem Cell Institute, CHA University, 606-16 Yoeksam 1-dong, Gangnam-gu, Korea

⁵These authors contributed equally to this work

*Correspondence: rlanza@advancedcell.com (R.L.), kskim@mclean.harvard.edu (K.-S.K.)

DOI 10.1016/j.stem.2009.05.005

To date, all methods to generate induced pluripotent stem cells (iPSCs) require the use of genetic materials and/or potentially mutagenic molecules. Here we report the generation of stable iPSCs from human fibroblasts by directly delivering four reprogramming proteins (Oct4, Sox2, Klf4, and c-Myc) fused with a cell-penetrating peptide (CPP). These protein-induced human iPSCs (p-hiPSCs) exhibited similarity to human embryonic stem cells (hESCs) in morphology, proliferation, and expression of characteristic pluripotency markers. p-hiPSC lines produced with these recombinant proteins were successfully maintained for more than 35 passages and differentiated into derivatives of all three embryonic germ layers both in vitro and in teratomas. This system eliminates the potential risks associated with the use of viruses, DNA transfection, and potentially harmful chemicals and in the future could potentially provide a safe source of patient-specific cells for regenerative medicine.

Over a decade ago, Wilmut and colleagues showed that adult somatic cells could be reprogrammed back to an undifferentiated embryonic state using somatic cell nuclear transfer (SCNT) (Wilmut et al., 1997). However, since that time, attempts to generate patient-specific cells using SCNT have proven unsuccessful (Chung et al., 2009; French et al., 2008). In 2006, a new and less controversial method of reprogramming somatic cells to pluripotency was reported by viral expression of the transcription factors Oct4, Sox2, Klf4, and c-Myc (Takahashi and Yamanaka, 2006). This and subsequent studies confirmed that mouse and human somatic cells can be reprogrammed to the pluripotent state via viral

transduction with the same or similar sets of reprogramming factors (Maherali et al., 2007; Okita et al., 2007; Park et al., 2008; Takahashi et al., 2007; Wernig et al., 2007; Yu et al., 2007). Although the therapeutic potential of iPSCs has been demonstrated in animal models of sickle cell anemia and Parkinson's disease (Hanna et al., 2007; Wernig et al., 2008), these cells contain multiple viral vector integrations that make them unsuitable for human clinical trials. The use of genome-integrating viruses could cause insertional mutagenesis and unpredictable genetic dysfunction (Okita et al., 2007; Yamanaka, 2007).

To address whether it is possible to generate hiPSCs without the use of viral or DNA vectors, we attempted to deliver four reprogramming proteins—Oct4, Sox2, Klf4, and c-Myc—directly into somatic cells. A major hurdle for intracellular delivery of macromolecules such as proteins is their limited ability to cross the cellular membrane (Belting et al., 2005). In 1988, Frankel and Pabo found that the human immunodeficiency virus transactivator of transcription (HIV-TAT) protein can overcome this hurdle with a short basic segment residing at amino acids 48–60 that allows this protein to penetrate the cell membrane and activate HIV-specific genes (Frankel et al., 1988; Frankel and Pabo, 1988). This and other naturally occurring peptides capable of overcoming the cell membrane barrier contain a high proportion of basic amino acids (e.g., arginine or lysine) and are known as CPPs (El-Sayed et al., 2009; Ziegler et al., 2005). In order to test our hypothesis that CPP-anchored reprogramming proteins may directly reprogram human somatic cells without genetic manipulation and/or chemical treatments,

we first examined whether red fluorescent protein (RFP) fused with a 9 arginine (RFP-9R) (Wender et al., 2000) could penetrate into COS-7 cells and human newborn fibroblasts (HNFs). RFP-9R was efficiently delivered into both cell types within a few hours, even when in the context of whole-cell extracts (see Figure S1 available online). We then generated stable HEK293 cell lines that could express each of the four human reprogramming factors (Oct4, Sox2, Klf4, and c-Myc) fused with 9R and the myc tag. High expression of these proteins was confirmed in HEK293 cell lines by western blotting analyses (Figure S2). When HNFs were treated with cell extracts from the HEK293 cell lines, efficient intracellular translocation of each recombinant protein was observed within 8 hr (Figure 1A). Notably, in contrast to RFP-9R, which was translocated to the cytoplasm, it appeared that most recombinant reprogramming proteins were translocated to the nucleus, while some remained in the cytoplasm (Figure 1A and Figure S1).

In an initial series of experiments, 5×10^5 HNFs were treated with combined total extracts of four HEK293 cell lines for 16 hr (see "Protocol 1" in Figure S3). After washing, cells were incubated for 6 days in ES media 1 and then transferred onto mouse embryonic feeders (MEFs). The transferred cells were incubated with ES media 2 for up to 4 weeks. Despite numerous attempts, we did not observe the formation of reprogrammed colonies using this protocol. We next treated with the same total extracts for 16 hr followed by washing and incubation with ES media 1 for 8 hr/day for 6 days ("Protocol 2" in Figure S3). By day 7, most cells did not survive, and no colonies

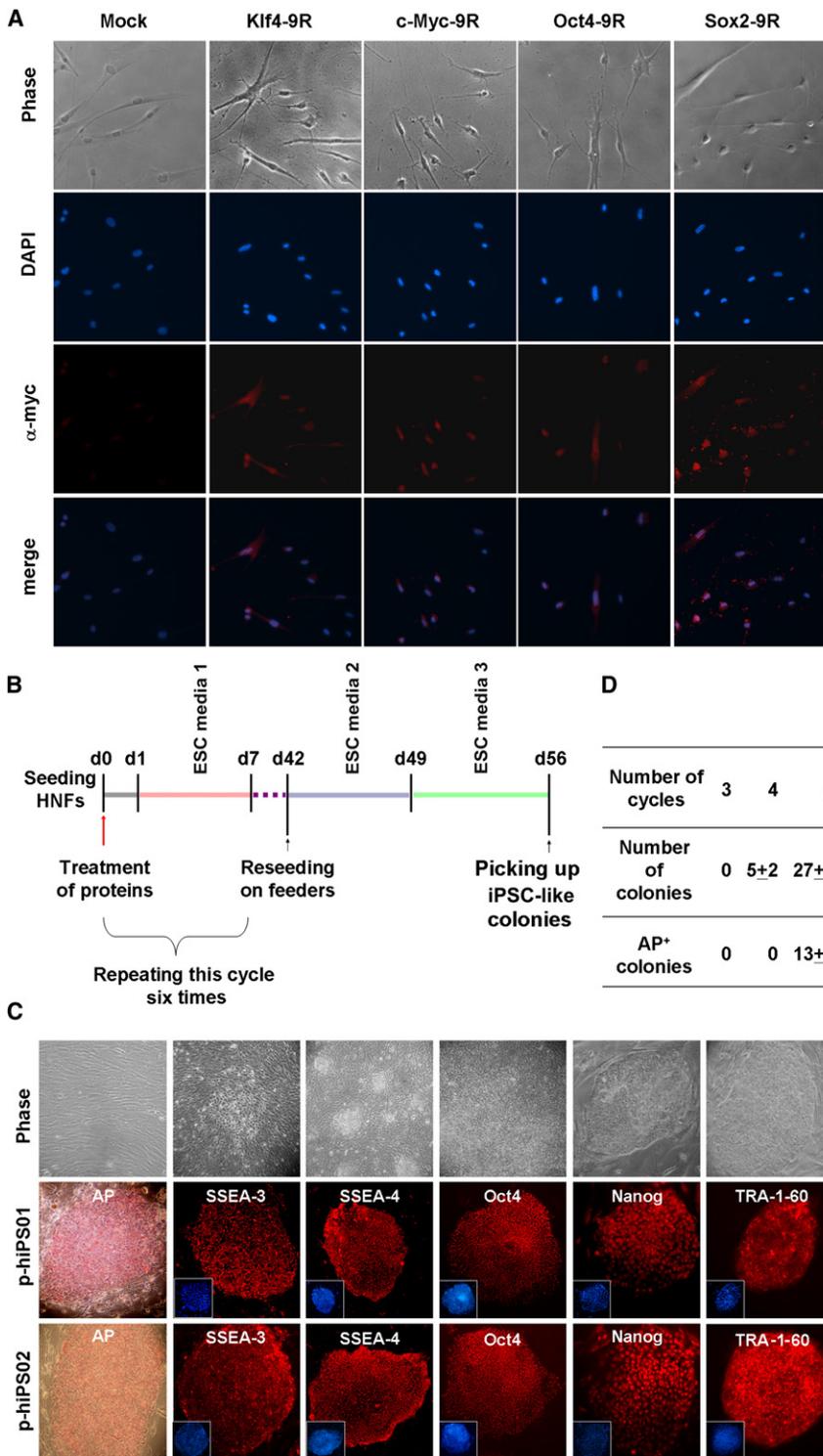


Figure 1. Generation of Protein-Induced hiPSC Lines by Direct Delivery of Reprogramming Proteins Fused with 9R as a CPP

(A) HNFs were incubated with HEK293 extracts expressing each reprogramming protein and subjected to immunocytochemistry using myc antibodies. Nuclei were counterstained with DAPI.
 (B) The schematic protocol depicts a repeated process and the timeline for generating p-hiPSCs from HNFs.
 (C) (Top panel) Shown are starting HNFs (first image), morphology after three cycle protein treatments (second image), and increased colony number after six cycles (third image). Approximately half of these iPS-like colonies stained positive for AP; early morphology after p-hiPSC colonies were transferred to

MEF. One potential reason for the lack of success is that, in contrast to virus- or other DNA-based methods, the reprogramming factors were not provided continuously and thus were in short supply. Therefore, we tested whether repeated protein treatment cycles (16 hr protein treatment followed by 6 day incubation in ES media 1) (Figure 1B) could yield hiPSCs. Using this approach, after three or four rounds of treatment, several colonies with iPSC-like morphology were observed (Figure 1C), although none of these colonies showed alkaline phosphatase (AP) activity, suggesting only rudimentary reprogramming. When this procedure was repeated for further cycles, the number of iPSC-like colonies significantly increased, and approximately half of the resulting colonies were AP positive starting from the sixth cycle (Figure 1D). In contrast, no such colonies were formed at any stage when extracts of naive HEK293 cells were used. AP-positive colonies with iPSC-like morphology were handpicked and transferred onto MEFs in the presence of ES media 2 and ES media 3 for 7 days each. Five hiPSC-like colonies were established, and two of them were maintained and characterized in this study. These two cell lines (p-hiPS01 and p-hiPS02) have been successfully maintained for more than 35 passages and exhibit morphology similar to that of hESCs, characterized by large nuclei and scant cytoplasm (Figure 1C). Overall, the establishment of these hiPSC-like colonies took about 8 weeks, approximately double that seen with viral transduction (Park et al., 2008; Takahashi et al., 2007; Yu et al., 2007). At present, the efficiency of hiPSC generation is significantly lower using this protein-based protocol (about 0.001% of input cells; Figure 1D), compared to virus-based

MEF is shown (fourth image); and morphology of established p-hiPSC line is shown at passage number 10 (p-hiPS01 [fifth image] and p-hiPS02 [sixth image]). Immunostaining of p-hiPS01 (middle panel) and p-hiPS02 (bottom panel) clones show expression of hESC markers, including AP, SSEA-3, SSEA-4, Oct4, Nanog, and TRA-1-60. Nuclei were stained with DAPI (blue in second and third row of panel).

(D) Shown is efficiency of reprogrammed colony formation with iPS-like morphology and AP-positive staining after different numbers of the protein treatment cycle. This is the summary of three independent experiments with the standard error.

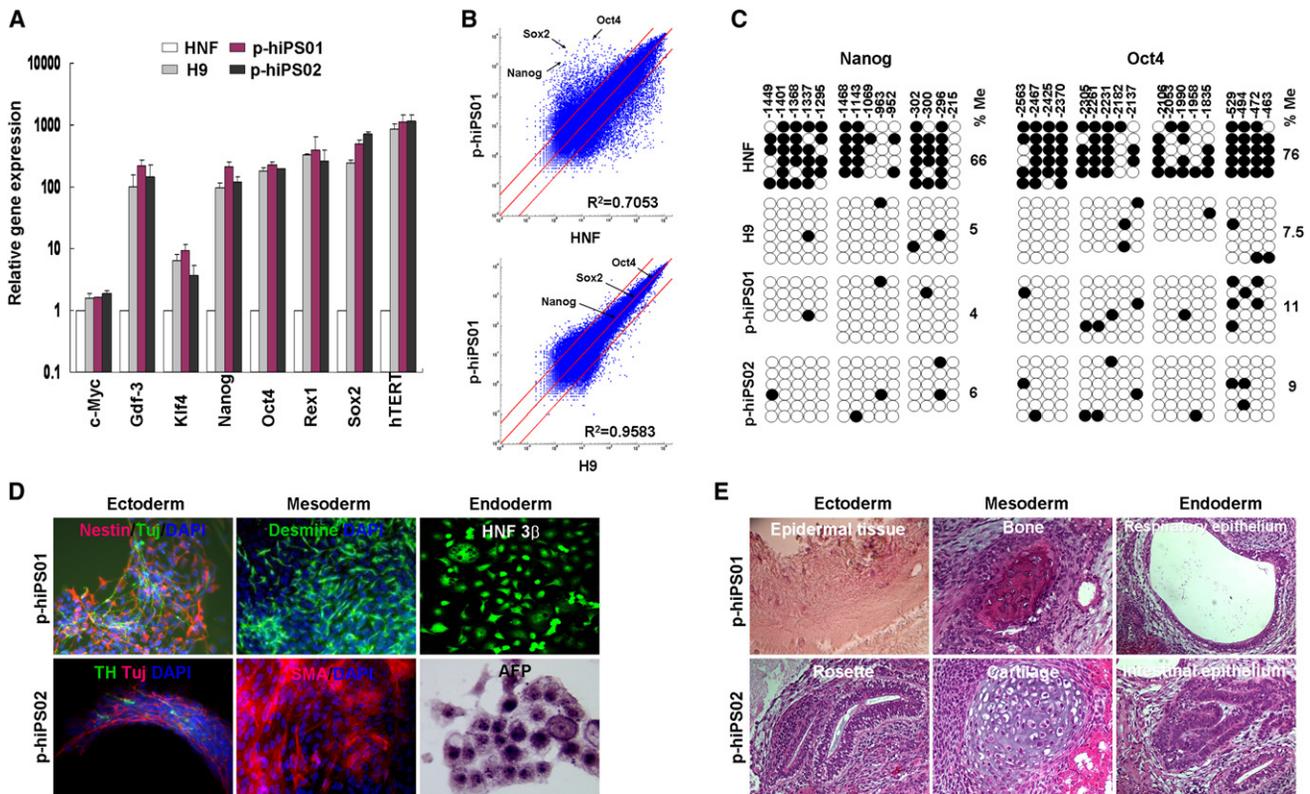


Figure 2. Characterization of p-hiPSC Lines

(A) Quantitative RT-PCR was performed to assess the expression of c-Myc, Gdf-3, Klf4, Nanog, Oct4, Rex1, Sox2, and hTERT in p-hiPS01 and p-hiPS02, hES (H9), and HNF cells. Relative gene expression represents fold changes relative to that of HNF cells normalized to β -actin expression. This experiment (repeated twice in triplicate using independently prepared cDNAs) resulted in almost identical patterns.

(B) The global gene-expression patterns were compared between p-hiPS01 and HNF, and between p-hiPS01 and H9 with Affymetrix microarrays. The red lines indicate the diagonal and 5-fold changes between the paired samples.

(C) Bisulfite sequencing analysis of the Nanog and Oct4 promoters reveals almost complete epigenetic reprogramming. Open and closed circles indicate unmethylated and methylated CpG, respectively. Numbers on top show each CpG location. Percentages of CpG methylation (%Me) are shown.

(D) In vitro differentiation of p-hiPSCs. Immunostaining images (first and second row panels) show all three germ layer cells at day 24, including neural (ectodermal), muscle and endothelial-like (mesodermal), and endoderm-like cells (endoderm).

(E) Teratoma formation in immunodeficiency mice by p-hiPSCs. H&E staining was performed for teratomas. The resulting teratomas contained tissues representing all three germ layers (p-hiPS01, first row; and p-hiPS02, second row): ectoderm, epidermal and neural tissue (rosette); mesoderm, bone and cartilage; and endoderm, respiratory epithelium and intestinal-like epithelium.

protocols (about 0.01% of input cells) (Park et al., 2008; Takahashi et al., 2007; Yu et al., 2007).

In order to determine whether the p-hiPSCs have hESC-like properties, we examined them for expression of markers of pluripotency. As shown in Figure 1C, both cell lines prominently expressed ESC markers, including AP, Oct4, Nanog, tumor-rejection antigen (TRA)1-60, stage-specific embryonic antigen (SSEA)-3, and SSEA-4. Quantitative reverse transcription PCR (qRT-PCR) analysis confirmed that both lines expressed endogenous mRNAs of ESC markers: Oct4, Nanog, Sox2, reduced expression 1 (Rex1), growth and differentiation factor 3 (Gdf3), and telomerase reverse transcriptase (hTERT) levels were dramatically higher than those of

HNF cells (up to 100-fold, and comparable to hESCs) (Figure 2A). The expression patterns of ESC pluripotency markers were indistinguishable from hESCs (H9), strongly suggesting that appropriate epigenetic reprogramming had occurred in the p-hiPSCs. Bisulfite sequencing analyses further showed that the promoter regions of the pluripotency genes Nanog and Oct4 were significantly demethylated in both p-hiPSC lines and the hESC H9 line, whereas the same regions were densely methylated in the parental HNF cells (Figure 2C). hiPSC lines from the starting HNFs were also generated using retroviral vectors expressing the same four reprogramming factors (Park et al., 2008; Takahashi et al., 2007; Yu et al., 2007). These cells displayed similar char-

acteristics and properties as the p-hiPSCs (Figure S4), and one of them (rv-hiPS01) was used as a control. When global gene expression was compared using the Affymetrix Array U133 Plus 2.0, analyzing over 47,000 human transcripts, both p-hiPSC and rv-hiPS01 showed high similarity to hES H9, but not to HNFs (Figure 2B, Figure S5). Since hES H9 and rv-hiPS01 were used as control cell lines, it was important to rule out the possibility that the new p-hiPSCs were derived from contaminating cells. RT-PCR analyses detected all four transgene mRNAs in rv-hiPS01 cells, but not in p-hiPS01 and p-hiPS02 cell lines (Figure S6). Furthermore, DNA fingerprinting demonstrated that the patterns of both p-hiPSC lines and rv-hiPS01 cells were identical to the

parental HNF cells but different from those of the hES (H9) cells and HEK293 cells (Figure S7), thus confirming that both p-hiPSC lines are derived from HNF cells. Both p-hiPSC lines exhibited the same karyotype as the starting HNF cells (Figure S8).

When the p-hiPSCs were allowed to form embryoid bodies (EBs) by suspension culture, they readily differentiated into cells of all three germ layers (Figure 2D, Figure S8). After 8 days, well-formed EB structures were observed from both p-hiPSC clones. When these EB-like structures were incubated on gelatin-coated tissue culture plates in ITSFn media for 15–25 days, they differentiated to a wide range of cell types, including neural, muscle, and endodermal cells, among others. Immunocytochemical analyses demonstrated the existence of different cell types positive for hepatocyte necrosis factor 3 β (HNF 3 β , endoderm marker), α -fetoprotein (AFP, endoderm marker), smooth-muscle actin (SMA, mesoderm marker), desmin (mesoderm marker), Tuj1 (ectoderm marker), nestin (ectoderm marker), and tyrosine hydroxylase (TH, ectoderm marker) (Figure 2D, Figure S8). In addition, teratoma formation was observed after transplantation of p-hiPSCs under the kidney capsule of nude mice for 6–8 weeks. These teratomas contained tissues from all three germ layers including neural tissues (ectoderm), epidermal tissues (ectoderm), striated muscle (mesoderm), adipose tissue (mesoderm), cartilage (mesoderm), respiratory epithelium (endoderm), and intestinal-like epithelial tissues (endoderm) (Figure 2E, Figure S8), confirming that both p-hiPSC clones exhibit pluripotency both in vitro and in vivo.

Protein-based hiPSC technology offers a new and potentially safe method for generating patient-specific stem cells that does not require the destruction of ex utero embryos. This system completely eliminates genome manipulation and DNA transfection, resulting in human iPSCs suitable for drug discovery, disease modeling, and future clinical translation. In this regard, the present study demonstrates the “proof of concept” that human iPSCs can be generated by direct protein delivery without genetic manipulation. Other studies suggest that it may be possible to replace and/or further reduce the number of factors required for reprog-

ramming (Huangfu et al., 2008; Li et al., 2009; Shi et al., 2008). To minimize/avoid chromosomal disruption, adenovirus and plasmid transfection have been successfully used to generate iPSCs in the mouse system (Kaji et al., 2009; Okita et al., 2008). Also, Thomson and his colleagues reported generation of hiPSCs by transfection with nonintegrating episomal vectors (Yu et al., 2009). In addition, *piggyBac* transposon (Kaji et al., 2009; Woltjen et al., 2009) and Cre-recombinase excisable viruses (Soldner et al., 2009) have been used to generate hiPSCs. While the transgenes can be excised by inducible gene expression once reprogramming is established (Soldner et al., 2009; Stadtfeld et al., 2008; Woltjen et al., 2009), residual sequences and chromosomal disruptions may still result in harmful alterations that could pose clinical risks.

The DNA vector-free, direct protein transduction system described here eliminates limitations that may be caused by viral or any other DNA-based reprogramming methods. However, the generation of p-hiPSCs is very slow and inefficient and requires further optimization. In particular, the whole-protein extracts used in the present study limited the concentrations of factors delivered into the target cells, thus suggesting that p-hiPSCs may be more efficiently generated using purified reprogramming proteins. Recently, Ding and his colleagues reported the generation of mouse iPSCs by combining the use of recombinant reprogramming proteins and the small molecule valproic acid (Zhou et al., 2009). In this study, mouse iPSCs were not generated when only recombinant proteins were used. In contrast, the system described here generated human iPSCs with direct delivery of reprogramming proteins in the absence of any chemical treatment. One possible explanation for these differences is that we used reprogramming proteins expressed in mammalian cells, while Ding and colleagues used refolded proteins after expression in *E. coli*. Since chemicals such as valproic acid and/or genetic manipulation may induce mutations, it has been suggested that whole genomic sequencing would be necessary if such methods are used to generate iPSCs (Yamanaka, 2009). In conclusion, the system described here eliminates the potential risks associated with chromo-

somal integrations and/or mutations and may allow the translation of hiPSC technology into the clinic.

ACCESSION NUMBERS

Microarray data can be assessed at Gene Expression Omnibus (<http://www.ncbi.nlm.nih.gov/geo/>) under accession numbers GSE16093, GSM402806, GSM402752, GSM402717, GSM402708, and GSM402707.

SUPPLEMENTAL DATA

Supplemental Data include Supplemental Experimental Procedures, Supplemental References, eight figures, and four tables and can be found with this article online at [http://www.cell.com/cell-stem-cell/supplemental/S1934-5909\(09\)00214-8](http://www.cell.com/cell-stem-cell/supplemental/S1934-5909(09)00214-8).

ACKNOWLEDGMENTS

This work was supported by National Institutes of Health (NIH) grants MH48866 and DC 006501 and by International Grants from the CHA University, Korean Stem Cell Research Center, and Dongyang Corporation Co. in Korea. The authors thank Dr. V. Morgan (Harvard Partners Center for Genetics and Genomics), Dr. J. Kim (Harvard Medical School), and Dr. J. Lee (Shippensburg University) for microarray analysis and Ms. J. Johnson (Cell Line Genetics) for karyotyping analysis. R.L. is an employee and shareholder of Advanced Cell Technology and a scientific advisor for Stem Cell and Regenerative Medicine International. K.Y.C. is a shareholder of CHA Bio and Diostech Co., Ltd., and Stem Cell and Regenerative Medicine International.

Received: May 6, 2009

Revised: May 11, 2009

Accepted: May 12, 2009

Published online: May 28, 2009

REFERENCES

- Belting, M., Sandgren, S., and Witttrup, A. (2005). *Adv. Drug Deliv. Rev.* 57, 505–527.
- Chung, Y., Bishop, C.E., Treff, N.R., Walker, S.J., Sandler, V.M., Becker, S., Klimanskaya, I., Wun, W.S., Dunn, R., Hall, R.M., et al. (2009) Cloning Stem Cells. Published online February 2, 2009. 10.1089/clo.2009.0004.
- El-Sayed, A., Futaki, S., and Harashima, H. (2009). *AAPS J.* 11, 13–22.
- Frankel, A.D., and Pabo, C.O. (1988). *Cell* 55, 1189–1193.
- Frankel, A.D., Bredt, D.S., and Pabo, C.O. (1988). *Science* 240, 70–73.
- French, A.J., Adams, C.A., Anderson, L.S., Kitchen, J.R., Hughes, M.R., and Wood, S.H. (2008). *Stem Cells* 26, 485–493.
- Hanna, J., Wernig, M., Markoulaki, S., Sun, C.W., Meissner, A., Cassidy, J.P., Beard, C., Brambrink, T., Wu, L.C., Townes, T.M., et al. (2007). *Science* 318, 1920–1923.
- Huangfu, D., Osafune, K., Maehr, R., Guo, W., Eijkelenboom, A., Chen, S., Muhlestein, W., and

- Melton, D.A. (2008). *Nat. Biotechnol.* 26, 1269–1275.
- Kaji, K., Norrby, K., Paca, A., Mileikovsky, M., Mohseni, P., and Woltjen, K. (2009). *Nature* 458, 771–775.
- Li, W., Wei, W., Zhu, S., Zhu, J., Shi, Y., Lin, T., Hao, E., Hayek, A., Deng, H., and Ding, S. (2009). *Cell Stem Cell* 4, 16–19.
- Maherali, N., Sridharan, R., Xie, W., Utikal, J., Eminli, S., Arnold, K., Stadtfeld, M., Yachechko, R., Tchieu, J., Jaenisch, R., et al. (2007). *Cell Stem Cell* 1, 55–70.
- Okita, K., Ichisaka, T., and Yamanaka, S. (2007). *Nature* 448, 313–317.
- Okita, K., Nakagawa, M., Hyenjong, H., Ichisaka, T., and Yamanaka, S. (2008). *Science* 322, 949–953.
- Park, I.H., Zhao, R., West, J.A., Yabuuchi, A., Huo, H., Ince, T.A., Lerou, P.H., Lensch, M.W., and Daley, G.Q. (2008). *Nature* 457, 141–146.
- Shi, Y., Desponts, C., Do, J.T., Hahm, H.S., Scholer, H.R., and Ding, S. (2008). *Cell Stem Cell* 3, 568–574.
- Soldner, F., Hockemeyer, D., Beard, C., Gao, Q., Bell, G.W., Cook, E.G., Hargus, G., Blak, A., Cooper, O., Mitalipova, M., et al. (2009). *Cell* 136, 964–977.
- Stadtfeld, M., Nagaya, M., Utikal, J., Weir, G., and Hochedlinger, K. (2008). *Science* 322, 945–949.
- Takahashi, K., and Yamanaka, S. (2006). *Cell* 126, 663–676.
- Takahashi, K., Tanabe, K., Ohnuki, M., Narita, M., Ichisaka, T., Tomoda, K., and Yamanaka, S. (2007). *Cell* 131, 861–872.
- Wender, P.A., Mitchell, D.J., Pattabiraman, K., Peckey, E.T., Steinman, L., and Rothbard, J.B. (2000). *Proc. Natl. Acad. Sci. USA* 97, 13003–13008.
- Wernig, M., Meissner, A., Foreman, R., Brambrink, T., Ku, M., Hochedlinger, K., Bernstein, B.E., and Jaenisch, R. (2007). *Nature* 448, 318–324.
- Wernig, M., Zhao, J.P., Pruszak, J., Hedlund, E., Fu, D., Soldner, F., Broccoli, V., Constantine-Paton, M., Isacson, O., and Jaenisch, R. (2008). *Proc. Natl. Acad. Sci. USA* 105, 5856–5861.
- Wilmut, I., Schnieke, A.E., McWhir, J., Kind, A.J., and Campbell, K.H. (1997). *Nature* 385, 810–813.
- Woltjen, K., Michael, I.P., Mohseni, P., Desai, R., Mileikovsky, M., Hamalainen, R., Cowling, R., Wang, W., Liu, P., Gertsenstein, M., et al. (2009). *Nature* 458, 766–770.
- Yamanaka, S. (2007). *Cell Stem Cell* 1, 39–49.
- Yamanaka, S. (2009). *Cell* 137, 13–17.
- Yu, J., Vodyanik, M.A., Smuga-Otto, K., Antosiewicz-Bourget, J., Frane, J.L., Tian, S., Nie, J., Jonsdottir, G.A., Ruotti, V., Stewart, R., et al. (2007). *Science* 318, 1917–1920.
- Yu, J., Hu, K., Smuga-Otto, K., Tian, S., Stewart, R., Slukvin, I.I., and Thomson, J.A. (2009). *Science* 324, 797–801.
- Zhou, H., Wu, S., Joo, J.Y., Zhu, S., Han, D.W., Lin, T., Trauger, S., Bien, G., Yao, S., Zhu, Y., et al. (2009). *Cell Stem Cell* 4, 381–384.
- Ziegler, A., Nervi, P., Durrenberger, M., and Seelig, J. (2005). *Biochemistry* 44, 138–148.