

PATHOBIOLOGY IN FOCUS

A practical guide to induced pluripotent stem cell research using patient samples

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Approximately 3 years ago, we assessed how patient induced pluripotent stem cell (iPSC) research could potentially impact human pathobiology studies in the future. Since then, the field has grown considerably with numerous technical developments, and the idea of modeling diseases ‘in a dish’ is becoming increasingly popular in biomedical research. Likely, it is even acceptable to include patient iPSCs as one of the standard research tools for disease mechanism studies, just like knockout mice. However, as the field matures, we acknowledge there remain many practical limitations and obstacles for their genuine application to understand diseases, and accept that it has not been as straightforward to model disorders as initially proposed. A major practical challenge has been efficient direction of iPSC differentiation into desired lineages and preparation of the large numbers of specific cell types required for study. Another even larger obstacle is the limited value of *in vitro* outcomes, which often do not closely represent disease conditions. To overcome the latter issue, many new approaches are underway, including three-dimensional organoid cultures from iPSCs, xeno-transplantation of human cells to animal models and *in vitro* interaction of multiple cell types derived from isogenic iPSCs. Here we summarize the areas where patient iPSC studies have provided truly valuable information beyond existing skepticism, discuss the desired technologies to overcome current limitations and include practical guidance for how to utilize the resources. Undoubtedly, these human patient cells are an asset for experimental pathology studies. The future rests on how wisely we use them.

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The potential influence of induced pluripotent stem cell (iPSC) technology for pathobiology studies is revolutionary.¹ Once established from any given patient, iPSCs serve as enduring resources to provide various functional cell types, essentially forever, which retain genomic information from the original patient. For this reason, as well as based upon expectations of their applications for cellular transplantation therapy, iPSC research has been growing exponentially within the short number of years since the original method was published by Takahashi and Yamanaka in 2006.² Technical feasibility and high reproducibility are two additional reasons why the method has prevailed worldwide so quickly. Fundamentally, iPSC generation does not require sophisticated equipment or technical expertise, and all the materials required for generation are

commercially available. Owing to more recent technological advances, one can now routinely generate iPSCs from patient peripheral blood cells without concern of exogenous gene integration. Accordingly, we can say iPSC technology has become a standard research tool in experimental medicine, like polymerase chain reaction, small interfering RNA, knockout mice and others.

Basic approaches to utilize patient iPSCs for disease mechanism studies are well demonstrated in the literature. Essentially, when patient iPSCs are differentiated into disease-relevant cell types, they can recapitulate, at least in part, molecular and phenotypic changes seen in patients. Using this system, we can further investigate how disease-related phenotypes develop ‘in a dish’, or even test whether novel therapeutic approaches can reverse these changes. Pioneering

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studies proved that these concepts are indeed valid for certain clinical disorders of both monogenic and polygenic origins. Thus, the future looks quite promising in general. However, when the concept is applied to model a wide range of diseases, we often encounter practical limitations and obstacles for their genuine application to understand diseases, and realize their application has not been as straightforward as initially proposed. First, despite numerous published protocols, *in vitro* differentiation of iPSCs is challenging, often requiring tremendous effort for optimization until the system becomes useful in other laboratories. Second, even after differentiation is successfully achieved, a major obstacle frequently resides in limited value of the *in vitro* outcomes, which may not closely represent disease conditions.

As we have witnessed triumphal examples and experienced many practical obstacles at the same time, we are gradually recognizing ways to utilize patient iPSCs more wisely. Three years have passed since we wrote the previous review in *Laboratory Investigation*,¹ and during this time, we have had the opportunity to manage a core facility for patient iPSC research at the University of Florida. Thus, we feel this is a good time to revisit the issue of ‘modeling diseases in a dish’ using patient iPSCs, and try to elucidate where we are now with the technology. We target general experimental pathologists as primary readers of the present review, particularly those who are interested in starting patient iPSC research to study a disease of their interest, but not yet sure whether the direction will justify the effort. As there are many outstanding review articles available for recent technological advances in iPSCs,^{3–5} here we will focus more on introducing practical issues and solutions for pathobiology applications, leaving extensive details to the references.

EXEMPLARY CASES

To understand how patient iPSC research is generally conducted, it is useful to introduce a few exemplary cases briefly, in which patient iPSCs have been wisely and beneficially utilized. As iPSCs retain genomic information from the original patient, theoretically we can analyze phenotypic and functional characteristics manifested from changes in the individual genome. Initially, early-onset monogenic disorders, where a single genetic aberration is considered to cause severe deleterious effect on cellular function, have been studied preferentially using iPSCs.

Early-Onset Monogenic Disease

An exemplary work proving the concept, ‘modeling diseases in a dish’ was first published in January 2009 by Ebert *et al.*⁶ The authors successfully established iPSCs from patients with spinal muscular atrophy, differentiated them into motor neurons, and demonstrated the premature death of neurons *in vitro*, a phenotype reflecting the disorder. Importantly, the study further proposed that disease iPSCs could be utilized to

screen novel drugs that could de-repress the *SMN2* gene, a close homolog of the mutated *SMN1* gene. *SMN2* is normally not expressed in neurons but could mitigate the disease phenotype when induced. It should be noted that the *SMN2* gene only exists in humans but not in rodents, thus this type of drug screening would only be possible using human neurons.

Late-Onset Monogenic Disease

Modeling late-onset disease in a dish is a more difficult task because some environmental factors, for example, oxidative stressors, may be involved in disease progression. Nevertheless, Nguyen *et al.*⁷ demonstrated, for instance, that a phenotype of a familial Parkinson’s disease (PD) can be evaluated *in vitro*. The authors generated iPSCs from a patient with a mutation in the leucine-rich repeat kinase 2 (*LRRK2*) gene and differentiated the iPSCs into dopaminergic neurons. The resultant dopaminergic neurons were more susceptible to oxidative stressors (hydrogen peroxide, MG-132 and 6-hydroxydopamine), compared with those from control iPSCs. The study also demonstrated that the patient iPSC-derived dopaminergic neurons had an increase in α -synuclein, which is one of the major components of Lewy bodies, a hallmark of PD pathology.

Proving the Causal Mutation and Elucidating a Novel Mechanism

LRRK2-G2019S is the most commonly identified mutation, but it is only found in a few percent of the sporadic PD patients. Genome-wide association studies suggested that many other polymorphisms in other genomic loci are linked to the disease phenotypes and clinical courses. To that end, the exact pathological mechanism caused by the *LRRK2-G2019S* mutation needed to be elucidated using isogenic controls. Reinhardt *et al.*⁸ applied genomic engineering technology to correct the *G2019S* mutation in patient iPSCs. They confirmed *LRRK2-G2019S* indeed induced pathological changes of dopaminergic neurons such as deficit in neurite outgrowth, defect in autophagy, increase in α -synuclein, and higher susceptibility to oxidative stress. Furthermore, the study demonstrated the *LRRK2-G2019S* mutation is associated with activation of extracellular signal-regulated kinases (ERKs), which leads to transcriptional dysregulation of *CPNE8*, *MAP7*, *UHRF2*, *ANXA1* and *CADPS2*, resulting in neural degeneration. By demonstrating an ERK inhibitor-mediated amelioration of the neurodegeneration, the study indeed indicated a novel therapeutic approach for patients with PD.

Polygenic Disorder or Disease of Unknown Causes

In the case of polygenic disorders or sporadic diseases with unknown causes, it is more challenging to obtain useful outcomes using patient-derived iPSCs. Israel *et al.*⁹ successfully investigated neural phenotypes derived from both familial and sporadic Alzheimer’s disease. One of the

	Helpful	Harmful
Internal Origin	<p>Strengths</p> <ul style="list-style-type: none"> <input type="checkbox"/> Clear merits to use patient iPSCs <input type="checkbox"/> Strong research history for the disease <input type="checkbox"/> Accessibility to number of patients (or iPSC clones) <input type="checkbox"/> Preexisting collaborative strengths to develop the study 	<p>Weaknesses</p> <ul style="list-style-type: none"> <input type="checkbox"/> May take time to establish differentiation protocols in your lab <input type="checkbox"/> Differentiated cells may not be pure or mature enough for your study
External Origin	<p>Opportunities</p> <ul style="list-style-type: none"> <input type="checkbox"/> High expectations for developing novel model systems <input type="checkbox"/> High expectations from societies of particular diseases <input type="checkbox"/> External and internal grant opportunities 	<p>Threats</p> <ul style="list-style-type: none"> <input type="checkbox"/> Competitors working on similar directions <input type="checkbox"/> Competing animal models

Figure 1 SWOT analysis before start patient iPSC research. It is critical to analyze all the strengths and potential problems you have before you initiate patient iPSC research. A local iPSC core facility may also assist you to analyze individual projects and create a research design.

two sporadic patient's iPSCs showed higher levels of the pathological markers amyloid- β (1-40), phosphor-tau(Thr231) and active glycogen synthase kinase-3 β (aGSK-3 β), as those derived from familial Alzheimer's disease, while the other case did not. These observations offered new opportunities to investigate the mechanisms underlying heterogeneity among sporadic cases. For such studies, however, a larger number of patients and controls would ideally be required.

Imprinting Disorders

In addition to genetic diseases, the iPSC models facilitate investigation of epigenetic-related diseases such as Beckwith-Wiedemann syndrome, Silver-Russell syndrome, Angelman syndrome and Prader-Willi syndrome. Unlike genetics based on the DNA sequence, epigenetic processes involve DNA methylation and histone modulation. One of the most important epigenetic phenomena is genomic imprinting by which genes are expressed in a parent-of-origin-specific manner. Abnormality of the imprinting mechanism during development causes epigenetic diseases. The methylation status of imprinting genes is maintained during iPSC generation and subsequent cultivation, implying that imprinting disease iPSCs are worth investigating to elucidate mechanism of imprinting abnormality.¹⁰ Patient iPSCs from Angelman and Prader-Willi syndrome have been established and utilized for examination of epigenetic and transcriptomic abnormalities, and for testing compounds aimed at correcting the epigenetic aberrations.^{11,12} One must use caution when analyzing epigenetic aberrations in imprinting disease iPSCs because the process of iPSC generation is associated with epigenetic dynamics that may bias interpretation.¹³ However, iPSCs with *in vitro* multipotency have been an invaluable tool to clarify molecular mechanisms as a simulator of developmental defects.^{14,15}

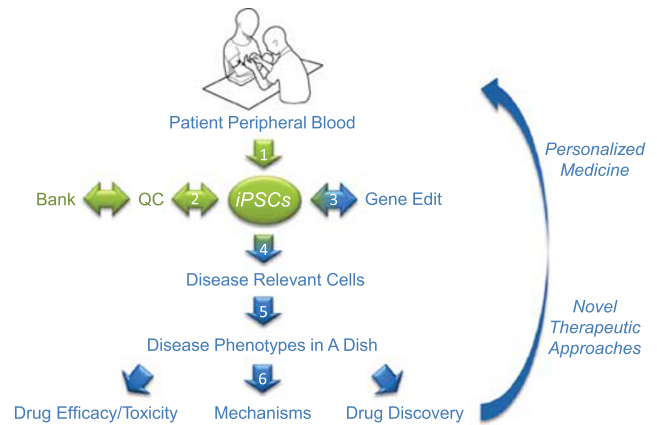


Figure 2 A typical work flow of patient iPSC research and tips for individual steps. (1) iPSC generation (~3 weeks)—multiple clones from multiple patients using non-integrating reprogramming vectors; (2) Quality control (QC) and storage (1–4 weeks)—first by morphology and pluripotency markers, then ideally by gene expression profiling, teratoma formation, karyotyping, and mycoplasma testing; (3) Isogenic controls made by gene editing serve as ideal controls; (4) Differentiation (2–10 weeks)—consult a local iPSC core or colleagues to identify the best available protocols; (5) Disease recapitulation—set realistic goals to demonstrate unique pathological changes *in vitro*; (6) Study further disease mechanisms—molecular ‘omic’ analyses are often used here. ‘Green’ highlighted parts are usually taken care by a local iPSC core facility (if desired), whereas ‘blue’ highlighted parts will typically be performed by individual investigators.

PRACTICAL ADVICE BEFORE YOU BEGIN

These exemplary cases certainly make us feel hopeful that we can apply patient iPSCs to various diseases. Taking all the progress and current issues into consideration, which we discuss more in detail in the following section, we have compiled practical tips you may find useful when starting patient iPSC research. First, it is essential to analyze whether the project is worth pursuing, as with any other new research projects. A SWOT analysis, for an example as shown in Figure 1, will guide you to identify the potential internal and external strengths and weaknesses of your direction. Unfortunately, the field is highly competitive, and the funding is scarce; thus it is critical to fully analyze the status of your project before beginning. In the end, the most important factor in the analysis is whether you have unique and significant question(s) that are likely answered using patient iPSCs.

When the analysis is positive, Figure 2 illustrates an actual workflow of the study with estimated time lines. Unless you have extensive experience in human pluripotent stem cell culture, it is easiest to consult with an iPSC core facility or colleagues to generate patient iPSCs. In a typical study of a monogenic disorder, generation of three iPSC clones from three individual patients is minimally required, along with an equivalent number of controls; however, such number can vary considerably depending on your questions. The quality of iPSC clones should also be controlled by the core facility to

Table 1 List of iPSC banks and registries by disease

Diseases	Institute	Website
General	Corriell Institute/NIGMS	http://ccr.coriell.org/Sections/Collections/NIGMS/ipsc_list.aspx?PgId=696
	American Type Cell Collection	http://www.atcc.org/Products/Cells_and_Microorganisms/Stem_Cells/Human_IPS_Pluripotent.aspx
	RIKEN Bioresource Center Cell Bank	http://www.brc.riken.jp/lab/cell/english/index_hps.shtml
	Wi-Cell	http://www.wicell.org/home/stem-cell-lines/order-stem-cell-lines/obtain-stem-cell-lines.cmsx
	Boston University, Center for Regenerative Medicine	http://www.bu.edu/dbin/stemcells/ips_cell_bank.php
	U MASS International Stem Cell Registry	http://www.umassmed.edu/iscr/Genetic-Disorders-Lines/
	U Connecticut Stem Cell Core	http://stemcellcore.uchc.edu/services/distribution.html
Neural	Harvard Stem Cell Institute	http://stemcelldistribution.harvard.edu/shoppingCart/index
	Corriell Institute/NINDS	http://ccr.coriell.org/Sections/Collections/NINDS/ipsc_list.aspx?PgId=711&coll=ND
Mental	NIMH Stem Cell Center	http://nimhstemcells.org/catalog.html

Currently available information of iPSC bank and registry (June 2014). Please note that the list here may not cover all the available sites.

meet the current standard, as discussed later. If patient iPSC clones or fibroblasts already exist in publicly available libraries, you can save substantial amount of time and cost. Table 1 shows a list of disease iPSC bank and registry, in which you may be able to find the lines of your interest. Additional information is available in a recent review article specifically discussing this topic.¹⁶

As we discuss later, iPSC differentiation should ideally be performed in collaboration between your lab and the iPSC core or a person who has iPSC expertise. In the steps of disease recapitulation and further mechanism studies, it is particularly important to set practical goals for patient iPSC research. First, you should accurately estimate purity, quantity and maturation status of the resultant iPSC-derived differentiated cells. Depending on those factors, you can identify what types of assays can be performed with the prepared cells. In general, patient iPSCs will hold the most value in identifying molecular changes caused by pathogenic mutations in certain human cell types. ‘Omic’ level screening will be particularly useful there; and isogenic iPSC clones with the mutation corrected through gene editing would serve as ideal controls in such tests, as discussed later.

TECHNICAL IMPROVEMENT AND REMAINING CHALLENGES

iPSC Generation

Viral methods

Methods for achieving reprogramming have progressed significantly from the groundbreaking work completed by Yamanaka and colleagues. The variety of reprogramming approaches stems from an interest to develop methods that do not integrate DNA into the host genome, making them feasible for eventual use in clinical applications. Virus-

mediated reprogramming is commonly used for its capacity to efficiently transduce cells of interest. Original methods using retrovirus^{2,17} and lentivirus¹⁸ remain widely used. The disadvantage is that these viruses integrate transgenes randomly into the host genome upon infection. This has the potential to cause unpredictable changes in the genome and result in aberrant transgene expression, which can potentially impact data interpretation and differentiation potential. Although scientists have devised ways to remove the transgenes after reprogramming is complete (using loxP sites and Cre recombinase),¹⁹ it is still necessary to thoroughly screen clones for confirmation of excision and loxP site retention that may alter endogenous gene expression. For these reasons, methods to reprogram cells have since focused on naturally non-integrating approaches.

Improvements using viruses that do not integrate into the genome, including adenovirus and Sendai virus, are becoming increasingly popular. The use of adenovirus was first applied to iPSC reprogramming shortly after the initial reprogramming reports.^{20,21} Adenovirus was chosen for its inability to integrate into the genome and ability to provide high transgene expression for a limited amount of time as the virus is reduced with each cell division. Although successful, the incidence of tetraploid cells following reprogramming has limited its usefulness.²⁰

Sendai virus has recently been developed for reprogramming because it is non-cytopathic and remains in the cytoplasm of host cells.²² In addition, it has the ability to reprogram peripheral blood mononuclear cells (PBMCs) in addition to other somatic cells (including fibroblasts). In addition to the non-integrating nature of this virus, it is cleared by culturing cells at an elevated temperature, or treatment with siRNA against the large protein (L-gene) of

the virus. Recently, a modification has also been introduced that enables clearance by microRNA 302L, naturally produced by pluripotent cells, which recognizes an inserted microRNA targeting sequence that was incorporated into the vector (Nakanishi, personal communication).

Non-viral methods

Non-viral methods include minicircle and episomal plasmids, piggyBac transposon, RNA transfection, protein transduction, and microRNA transfection. Traditional transfection was successfully used to reprogram mouse cells using polycistronic plasmids.^{23,24} However, extensive screening was necessary to find clones without integration. In addition, repeated transfections were necessary to maintain high transgene expression. Minicircle DNA was first applied to reprogram adipose stem cells.²⁵ Polycistronic minicircle is advantageous because transfection efficiency is improved and it is diluted out more slowly during cell division, thus reducing the number of transfections required. Unfortunately, both conventional and minicircle DNA reprogram at much lower efficiency and also require more hands on time due to multiple transfections. Episomal plasmids can be stably introduced into cells using drug selection, and can be removed after drug selection is discontinued. Yu *et al*²⁶ first showed feasibility of this method in 2009 by reprogramming human foreskin fibroblasts, although unfortunately this method also yielded low efficiency. The piggyBac transposon system enables the removal of all exogenous elements, cleaner than the Cre-loxP system. In 2009, multiple groups demonstrated high efficiency reprogramming using tetracycline-inducible or polycistronic expression of the reprogramming factors.^{27–29} Although removal of the transgenes was demonstrated by sequencing, transposase-mediated excision of transgenes was shown to also induce microdeletion of genomic DNA, which could pose a problem for future use.

Methods described thus far carry the risk of unexpected persistence or genetic modification. To circumvent this, scientists have been devising methods, which do not introduce DNA into the host cell. mRNA synthesized *in vitro* from cDNA of the reprogramming factors was demonstrated to be successful in 2010.³⁰ This method utilized host cells translation machinery, although it requires five consecutive transfections to be successful. Protein delivery is an alternative to nucleic acid introduction. Harnessing the ability of reprogramming factors tagged with C-terminus poly-arginine domains to transduce through the cell membrane, two groups showed feasibility.^{31,32} Protein delivery method eliminates the need to screen for integration of transgenes. However, efficiency was lower, and multiple rounds of transduction were necessary. In 2011, mature double-stranded microRNA including mir-200c, mir-302s and mir369s family of microRNAs were shown to reprogram somatic cells by direct transfection.³³ Although this method

resulted in lower efficiency, it provides a viable method compatible with clinical use.

Ultimately, these methods and modifications have laid the groundwork for improving methodology. Combination of these methods with small molecules has been shown to improve reprogramming. In 2013, Deng's group used a cocktail of seven compounds to reprogram mouse somatic cells into iPSCs at efficiency comparable to standard reprogramming techniques.³⁴ The ability to apply this technique to human cells would be an exciting advance in the field. Although many methods focus on efficiency, it is important to note that efficiency alone is not the most important aspect of the reprogramming process. In the end, it is more important to obtain a number of high quality iPSCs clones. Generally, fewer than 10 clones per individual are needed, especially if using a non-integrating method where exhaustive transgene screening is not necessary.

Practical considerations

Starting cell type before reprogramming is an important consideration. Dermal fibroblasts and PBMCs are the most common starting cells, and while most methods nearly always reprogram dermal fibroblasts successfully, using a method that also works for PBMCs increases flexibility. Benefits include reduced processing time (biopsy outgrowth can require up to 1 month *vs* isolation of PBMCs from a blood draw can be completed within an hour). In addition, a blood draw is less invasive and particularly useful for obtaining cells from pediatric patients. Ultimately, starting cell type may vary depending on the questions to be asked. If initial assays using fibroblasts can be useful for disease understanding, it may be advantageous to reprogram those cells. Regardless of delivery method (virus, plasmid and so on), utilizing polycistronic plasmids to introduce all reprogramming factors at once is easier and increases the likelihood of successfully reprogramming.

Commercial availability of multiple reprogramming methods is also increasing. Although cost may be an issue, it is possible to send samples to be reprogrammed using various non-integrating methods or to purchase ready to use reagents to complete the procedure in the lab. In addition, it is important to realize the reprogramming process itself is not the only barrier to overcome. It is imperative to learn proper culture techniques. To this end, many commercially available cell culture media are available (Life Technologies, ReproCell, Stem Cell Technologies and so on) that can ease the transition for researchers who are new to the culture techniques required to propagate these cells. Even for seasoned scientists, commercial protocols and products enable quick improvements and it is advantageous to keep up to date to reduce labor and improve quality of iPSC culture.

In addition to various culture media, there are also a number of different substrate iPSCs can be cultured on (mouse embryonic fibroblasts, Matrigel, Vitronectin, Geltrex and so on). In addition, iPSCs themselves are generally an

intermediate resource before differentiation to various lineages. As such, the vast variety of differentiation protocols generally has different starting cell culture conditions. Usually, these are referred to as feeder dependent or feeder free. For this reason, it may be advantageous to generate frozen stocks cultured by feeder-dependent and feeder-free techniques to reduce the labor involved if testing out a number of protocols.

Quality Control

Variability within iPSC clones (either genetic, epigenetic or phenotypic) has been a concern in patient iPSC research. Unless each iPSC clone is carefully evaluated, researchers could potentially run into issues with data misinterpretation when using this approach.

Quest for genome stability

To investigate characteristics of iPSCs derived from monogenic disorders, one of the important issues is to validate retention of the gene mutation in iPSCs and to identify additional mutations introduced during iPSC generation. By comparing genomes of parental cells and iPSCs, exome analysis may be a prerequisite for subsequent medical research of pathogenesis and drug discovery. Whole-exome analysis covering protein-coding sequences is sufficient to investigate pre-existing and additional mutations, although the recent platform of exome analysis has expanded to include not only coding but also untranslated, non-coding RNA and their adjacent regions. The number of single-nucleotide mutations per cell genome was estimated from 22 human iPSCs by extensive exome analysis on protein-coding sequences.³⁵ Generally, iPSCs are considered to have a comparable nucleotide substitution rate independent of donor cells, except for cells from patients with a genome instability syndrome, a DNA repair disorder or a DNA damage response syndrome. However, acquisition of novel mutations during passages is indeed unavoidable, and banking of early passage iPSC clones is therefore essential once suitable disease iPSCs are established and characterized.

Quest for quality control

In addition to genomic analysis, general characteristics of disease iPSCs such as morphological analysis, *in vitro* differentiation by embryoid body formation, teratoma formation by injection of iPSCs into immunodeficient animals, karyotypic analysis, short tandem repeat analysis, pluripotency markers such as Oct4/3, Sox2, Nanog, SSEA4, Tra-1-60 and Tra-1-81, and gene expression of exogenous and endogenous pluripotency-associated genes are usually performed. Before banking, contamination of mycoplasma, bacteria, virus and endotoxins should ideally be tested. Generally, morphology of iPSCs provides us enormous information including purity, quality, transformation, undifferentiated state and other cell contamination. In addition to these standard quality controls, profiling of RNA

expression, DNA methylation and glycans can be added for monitoring when necessary.^{10,13,36,37} These comprehensive analyses would also elucidate pathogenic states such as aberrant genomic methylation and gene expression of patient iPSCs.

Quest for suitable controls of disease iPSCs

In addition to disease-derived iPSCs, preparation of suitable control iPSCs are required for elucidation of disease mechanisms and drug discovery. One of the ideal controls is genetically corrected iPSCs. To correct gene mutation in disease iPSCs, ZFN, TALEN and CRISPR/Cas-based methods for genome editing can be used. Alternatively, introduction of exogenous genes that are mutated in disease iPSCs may be used, but the expression level of the exogenous gene may bias phenotypes. Another control is iPSCs obtained from the same age, gender and ethnic group. Usually, iPSCs from more than three independent patients and from more than three independent healthy donors need to be analyzed to conclude that observed pathogenic phenotypes are due to endogenous genotypes of the disease iPSCs. However, genetic correction and preparation of age-, gender- and ethnic-matched controls is labor intensive. To circumvent this, commonly available iPSCs from healthy donors may be used for comparison. MRC5-derived (fetal lung fibroblast) iPSCs have been utilized as a control in several previous reports,^{13,37-41} and can be obtained from the public bank. If MRC5-iPSCs do not demonstrate pathogenic phenotypes that disease iPSCs do under the same experimental condition, MRC5-iPSCs would serve as a practical control.

Differentiation

Lack of practical differentiation protocols

Depending on the desired disease or field of study, there may be ample protocols for investigators to turn to (as in the case of neurodegenerative disease modeling).^{3,5} However, unless the particular lab is well versed in the biology of both pluripotent stem cells and differentiated cell types, the likelihood of reproducing a protocol in a reasonable time is uncertain. In general, differentiation protocols take advantage of particular cytokines, culture media and extracellular matrices, thus making these protocols quite expensive. Often, after differentiation, cell populations of interest need to be separated using specific surface markers to achieve sufficient purity. In addition to the expense, most protocols are time consuming and slow in data collection. In general, common obstacles in published differentiation protocols include low reproducibility, low yield, high cost and multiple steps, which often utilize complicated procedures. Thus, except for a few relatively straightforward lineages such as neural progenitors, we are still lacking very practical protocols to prepare a large number of disease-relevant cell types. Developing simple, easy and affordable methods, where the process can be applied to robust

large-scale cell differentiation from patient iPSCs, is truly desired in the field.

Uncertain quality of differentiated cells

Depending on the cell type, iPSC differentiated cells may not proliferate well in the long term. As with human primary cells, doubling times while maintaining proper phenotype will most likely be limited, making it more difficult to carry out desired experiments. Furthermore, the possibility of freezing a batch of cells for later use may be unrealistic, giving investigators a 'one shot' per differentiation scenario to obtain meaningful data. This can become taxing if a differentiation protocol takes months from start to finish as in the case of vascular cell differentiation with a 2-month long protocol.⁴² Also, unless the differentiation protocol is well established in an investigator's own hands, a portion of the obtained cells will need to be used to assess the proper phenotype. Despite a successful differentiation protocol, investigators may run into issues if these cells are to be used in functional assays. iPSC-derived cells may have the proper phenotype but may be too immature to also possess the normal function of the cells. In that case, investigators will have to optimize such conditions for their specific interests keeping in mind the physiological relevance of their *in vitro* assays.

Practical considerations

Although there remain many issues to be improved, some iPSC differentiation protocols are relatively straightforward, and have been successfully used by multiple groups to obtain mesoderm,^{42–44} endoderm⁴⁵ and ectodermal^{46–48} lineages. These protocols utilize available materials, the procedures are uncomplicated, the methods include simple cell purification steps such as sorting, and their reproducibility and usefulness have been demonstrated by other investigators. There are many additional protocols available in the literatures (many that share commonalities, while others are distinct). As the field is constantly changing, updated information is best obtained through an iPSC core facility or colleague scientists. We emphasize here again that one should try to reproduce the protocol(s) in a side-by-side collaboration with a scientist who has expertise in iPSCs and another scientist with experience of the targeted differentiating lineage. Knowing the biology of both ends, the cells you start with and those you end up with, is critical to reproducing protocols in a reasonable time.

Disease Modeling

How to fill the discrepancies from real disease

Although generation of disease-relevant cell types from patient-derived iPSC is a standard strategy for studying a 'disease in a dish' as described above, many human diseases arise from multicellular interactions in the context of tissue architecture, organ or whole-body homeostasis. Therefore, it is essential to further advance model systems to represent a more complex physiological environment similar to the body.

When your hypothesis requires the interactions of different cell types for pathogenesis, multiple cell types in a co-culture setting will certainly provide further functional insights for the disease. As an exemplary work, the co-culture of glial cells from ALS iPSCs with neurons from normal iPSCs demonstrated the non-cell autonomous effect of diseased glial cells for aberrant survival of neurons.⁴⁹ Similarly, aberrant controls in vasculature tone would be better understood when co-culturing endothelial and vascular smooth muscle cells together rather than using a single cell type.

Admirably, iPSCs possess pluripotency comparable to embryonic stem cells (ESCs), which are originated from the embryonic blastocyst stage embryo. Both iPSCs and ESCs are competent to early developmental cues. Once proper cues are given, initial specification occurs to induce differentiation. The multiple types of differentiated cells are autonomously organized and interact with each other leading to subsequent fate specification like the cascade of embryonic development. To take maximum advantage of this self-organizing ability of pluripotent stem cells, several groups have developed sophisticated 3D culture protocols for making organoid structures *in vitro*. One example is the so-called 'mini-brain' consisting of tissue layers that mimic the brain cortex. Using this culture technique, Knoblich's group demonstrated that iPSCs derived from a microcephalic patient indeed formed a smaller brain than iPSCs from a healthy control.⁵⁰ Similarly, several organoid culture techniques for iPSCs have evolved to generate other tissue types and organs (optic cup, pituitary gland).^{51,52} Lack of vascular supply is the major limiting factor to grow more functional units in organoid culture. Remarkably, Taniguchi's group was able to generate a transplantable small liver unit from human iPSCs. They co-cultured hepatic endoderm cells differentiated from iPSC with human mesenchymal stem cells and human umbilical vein endothelial cells in a loosely solidified extracellular matrix. These cells autonomously formed the functional units of the liver *in vitro* with the support of microvasculature. Upon transplantation of the unit into immunodeficient mice, the liver bud quickly connected to the host vascular networks and further functional maturation occurred.⁵³

Advances in differentiation protocols heavily rely on our knowledge of the molecular mechanisms of embryonic development. Our knowledge is not sufficient to provide the optimal environment for desired morphogenesis from iPSC *in vitro* culture. Nevertheless, simple inoculation of iPSCs into immunodeficient animals is able to form teratomas, which comprise cells from all three germ layers (endoderm, mesoderm and ectoderm). As mature tissue organization (gut epithelial, cartilage and so on) can be observed in the tumor, it will be feasible to assess the histopathological phenotype of patient-derived iPSC using this methodology. For instance, iPSCs from dominant genetic disorders with oncogenesis may develop cancer in teratomas over time. Patients with familial adenomatous polyposis develop

adenoma and adenocarcinoma in colon. Similarly, iPSCs from familial adenomatous polyposis may generate adenoma and adenocarcinoma in colon-like mucosa in teratomas. iPSCs from degenerative disorders may exhibit degeneration or apoptosis of cells in corresponding tissues of teratomas. It is also noteworthy that histopathological analysis of implanted cells into immunodeficient animals may support *in vitro* phenotypes of iPSCs during the differentiation process.

To model systemic disease, it is compelling to reconstitute the human pathological process in experimental animals. For example, type I diabetes is recognized as a type of auto-immune disease, in which three major cell lineages (hematopoietic cells, pancreatic β cells and thymus epithelial cells) have important roles. Melton's group has reconstituted the human version of these three lineages into animals by transplantation into immunodeficient mice.⁵⁴ A more rigorous approach is led by Nakauchi's group, where they successfully generated a whole kidney or pancreas derived from iPSCs in the pig by blastocyst complementation. They transferred donor pig iPSC into pancreatogenesis- or nephrogenesis-disabled blastocyst stage pig embryos, and demonstrated the embryos were born as chimeras having pancreas or kidney exclusively derived from the donor pig iPSCs.⁵⁵ Any blastocyst complementation using human iPSC into animals has not been performed yet because of ethical issues, but theoretically it is feasible to generate whole functional human organs in animals using the same strategy. This humanized animal or hybrid animal approach using patient-derived iPSC would be a next-generation disease model for studying human pathology.

Gene Editing

Rapidly evolving gene-editing technology has been shown valuable in patient iPSC research as well, as described above with an exemplary case.

TALEN

Transcription activator-like effector nucleases (TALENs) are composed of a DNA-binding domain that is capable of directing the *FokI* nuclease to a specific target site. Two TALENs, recognizing left and right arms of the target site, respectively, can bring two *FokI* monomers close together for the formation of a functional dimer, which generates a DNA double-strand break (DSB) on the target site.^{56,57} The TALEN-induced DSBs activate the DNA repair system within cells, which stimulates non-homologous end joining (NHEJ) in the absence of a homologous DNA template. The error-prone nature of this repair mechanism results in the introduction of nucleotide mismatches, insertions or deletions. However, in the presence of a homologous template DNA, the DSB triggers homologous recombination, introducing desired DNA sequence alterations. The TALENs have rapidly gained prominence as a novel genome-editing tool, which were successfully applied to create site-specific gene modifications in model organisms such as yeast, plants, zebra fish, mouse, rat and human cells, including

human pluripotent cells.^{58–62} TALEN has also been used to generate single base-pair mutations, linking single-nucleotide polymorphisms to specific human disease.⁶³ Furthermore, TALENs have even been utilized to eliminate the mutant form of mitochondrial DNA from patient-derived cells.⁶⁴ Currently, TALEN plasmids targeting 18 740 protein-coding human genes have been assembled using a high-throughput Golden-Gate cloning system.⁶⁵ Delivery of these TALENs can be achieved by injection of DNA or mRNA encoding TALENs or even the TALEN proteins directly.^{62,66,67}

CRISPR

The CRISPR system is another effective genome-editing tool, which utilizes Cas9 nuclease to cleave DNA and chimeric guide RNA (gRNA) to target Cas9 to a specific region in the genome.^{68,69} The Cas9-gRNA-mediated genome editing has been shown to have improved efficiencies over TALENs and it is also easier to implement.^{68–72} Moreover, it allows simultaneous editing of more than one site through expression of multiple gRNAs.^{68,69} This approach was used to create mice carrying five different mutant genes in a single step,⁷³ and also was shown to generate large deletions of genomic regions by directing Cas9 cleavages at the two sites flanking the desired deletion.⁶⁸ Wu *et al*⁷⁴ have even shown in mice that a dominant mutation in *Crygc* gene that causes cataracts could be rescued by a Cas9-mediated DSB on the mutant allele, which triggered homology-directed repair based on the endogenous WT allele. More recently, a clone library encoding short gRNAs targeting all open reading frames in the human genome has been generated. Combined use of this library with Cas9 enabled the generation of random gene knockouts in the human genome, which can be screened for desired phenotypes to link genes to their functions.^{75,76} The CRISPR technology has been used to cure a mouse model of a human fatal liver disorder (type I tyrosinemia) caused by a single genetic mutation in the fumarylacetoacetate hydrolase gene.⁷⁷ This defect in tyrosine catabolism causes toxic accumulation of the amino acid, leading to liver failure. CRISPR-mediated genome editing could one day help treat many diseases caused by single mutations, such as hemophilia and Huntington's disease.

A mutant version of the Cas9 was further reported which cleaves only one strand of the target DNA, generating single-strand nicking, thus favors HR DNA repair over NHEJ (error prone), increasing desired DNA changes over random mutations.⁷⁰ Recently, a nuclease-defective Cas9 enzyme has been utilized to label genomic loci, allowing for visualization of *in vivo* of their partitioning in live cells.⁷⁸ Most interestingly, the catalytically inactive Cas9 nuclease, in complex with a gRNA, can bind to a specific site, which physically blocks the RNA polymerase, thus silencing the target gene.⁷⁹ Similarly, the catalytically inactive Cas9 was fused to known transcriptional activator domains and targeted to specific promoter regions by corresponding gRNAs, upregulating the target gene expression.⁸⁰ The

ability to artificially control the expression of specific target genes not only enables us to better understand gene functions but also to manipulate cell fate through controlled expression of desired sets of pathway genes.

CONCLUDING REMARKS

Undoubtedly, patient iPSCs are an enduring asset for experimental pathology studies, with some exemplary applications introduced above and many more in published literature. Additional technical improvement, particularly in iPSC differentiation methods and three dimensional cultures, as well as expansion of patient iPSC banking, will further accelerate the field. From a pathologist perspective, patient iPSC banking will serve as a powerful addendum to existing tissue banks. Their value is unlimited, as once established, they serve as an enduring and expandable resource for live patient cells. For instance, it is almost impossible to obtain hepatocytes from a rare metabolic disease through liver biopsy of a large number of patients at one given time and place. However, through iPSC banking, such resources will be available to any researcher, any place in the world, and at any time. Banking iPSCs of large patient cohorts with a clinical and GWAS database would be particularly useful in order to identify molecular mechanisms underlying certain genetic links to the disease or individual patients' drug efficacy and toxicity. The future rests on how properly we prepare the resource and how wisely we use it.

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- Hankowski KE, Hamazaki T, Umezawa A, *et al*. Induced pluripotent stem cells as a next-generation biomedical interface. *Lab Invest* 2011;91:972–977.
- Takahashi K, Yamanaka S. Induction of pluripotent stem cells from mouse embryonic and adult fibroblast cultures by defined factors. *Cell* 2006;126:663–676.
- Sandoe J, Eggan K. Opportunities and challenges of pluripotent stem cell neurodegenerative disease models. *Nat Neurosci* 2013;16:780–789.
- Cherry AB, Daley GQ. Reprogrammed cells for disease modeling and regenerative medicine. *Annu Rev Med* 2013;64:277–290.
- Tabar V, Studer L. Pluripotent stem cells in regenerative medicine: challenges and recent progress. *Nat Rev Genet* 2014;15:82–92.
- Ebert AD, Yu J, Rose Jr. FF, *et al*. Induced pluripotent stem cells from a spinal muscular atrophy patient. *Nature* 2009;457:277–280.
- Nguyen HN, Byers B, Cord B, *et al*. LRRK2 mutant iPSC-derived DA neurons demonstrate increased susceptibility to oxidative stress. *Cell Stem Cell* 2011;8:267–280.
- Reinhardt P, Schmid B, Burbulla LF, *et al*. Genetic correction of a LRRK2 mutation in human iPSCs links parkinsonian neurodegeneration to ERK-dependent changes in gene expression. *Cell Stem Cell* 2013;12:354–367.
- Israel MA, Yuan SH, Bardy C, *et al*. Probing sporadic and familial Alzheimer's disease using induced pluripotent stem cells. *Nature* 2012;482:216–220.
- Hiura H, Toyoda M, Okae H, *et al*. Stability of genomic imprinting in human induced pluripotent stem cells. *BMC Genet* 2013;14:32.
- Yang J, Cai J, Zhang Y, *et al*. Induced pluripotent stem cells can be used to model the genomic imprinting disorder Prader-Willi syndrome. *J Biol Chem* 2010;285:40303–40311.
- Chamberlain SJ, Chen PF, Ng KY, *et al*. Induced pluripotent stem cell models of the genomic imprinting disorders Angelman and Prader-Willi syndromes. *Proc Natl Acad Sci USA* 2010;107:17668–17673.
- Nishino K, Toyoda M, Yamazaki-Inoue M, *et al*. DNA methylation dynamics in human induced pluripotent stem cells over time. *PLoS Genet* 2011;7:e1002085.
- Cruvinel E, Budinetz T, Germain N, *et al*. Reactivation of maternal SNORD116 cluster via SETDB1 knockdown in Prader-Willi syndrome iPSCs. *Hum Mol Genet* 2014 (e-pub ahead of print).
- Martins-Taylor K, Hsiao JS, Chen PF, *et al*. Imprinted expression of UBE3A in non-neuronal cells from a Prader-Willi syndrome patient with an atypical deletion. *Hum Mol Genet* 2014;23:2364–2373.
- McKernan R, Watt FM. What is the point of large-scale collections of human induced pluripotent stem cells? *Nat Biotechnol* 2013;31:875–877.
- Takahashi K, Tanabe K, Ohnuki M, *et al*. Induction of pluripotent stem cells from adult human fibroblasts by defined factors. *Cell* 2007;131:861–872.
- Yu J, Vodyanik MA, Smuga-Otto K, *et al*. Induced pluripotent stem cell lines derived from human somatic cells. *Science* 2007;318:1917–1920.
- Soldner F, Hockemeyer D, Beard C, *et al*. Parkinson's disease patient-derived induced pluripotent stem cells free of viral reprogramming factors. *Cell* 2009;136:964–977.
- Stadtfeld M, Nagaya M, Utikal J, *et al*. Induced pluripotent stem cells generated without viral integration. *Science* 2008;322:945–949.
- Zhou W, Freed CR. Adenoviral gene delivery can reprogram human fibroblasts to induced pluripotent stem cells. *Stem Cells* 2009;27:2667–2674.
- Nishimura K, Sano M, Ohtaka M, *et al*. Development of defective and persistent Sendai virus vector: a unique gene delivery/expression system ideal for cell reprogramming. *J Biol Chem* 2011;286:4760–4771.
- Okita K, Nakagawa M, Hyenjong H, *et al*. Generation of mouse induced pluripotent stem cells without viral vectors. *Science* 2008;322:949–953.
- Gonzales F, Monasterio MB, Tiscornia G, *et al*. Generation of mouse-induced pluripotent stem cells by transient expression of a single nonviral polycistronic vector. *Proc Natl Acad Sci USA* 2009;106:8918–8922.
- Jia F, Wilson KD, Sun N, *et al*. A nonviral minicircle vector for deriving human iPS cells. *Nat Methods* 2010;7:197–199.
- Yu J, Hu K, Smuga-Otto K, *et al*. Human induced pluripotent stem cells free of vector and transgene sequences. *Science* 2009;324:797–801.
- Kaji K, Norrby K, Paca A, *et al*. Virus-free induction of pluripotency and subsequent excision of reprogramming factors. *Nature* 2009;458:771–775.
- Woltjen K, Michael IP, Mohseni P, *et al*. PiggyBac transposition reprograms fibroblasts to induced pluripotent stem cells. *Nature* 2009;458:766–770.
- Yusa K, Rad R, Takeda J, *et al*. Generation of transgene-free induced pluripotent mouse stem cells by the piggyBac transposon. *Nat Methods* 2009;6:363–369.
- Yakubov E, Rechavi G, Rozenblatt S, *et al*. Reprogramming of human fibroblasts to pluripotent stem cells using mRNA of four transcription factors. *Biochem Biophys Res Commun* 2010;394:189–193.
- Kim D, Kim CH, Moon JI, *et al*. Generation of human induced pluripotent stem cells by direct delivery of reprogramming proteins. *Cell Stem Cell* 2009;4:472–476.
- Zhou H, Wu S, Joo JY, *et al*. Generation of induced pluripotent stem cells using recombinant proteins. *Cell Stem Cell* 2009;4:381–384.
- Miyoshi N, Ishii H, Nagano H, *et al*. Reprogramming of mouse and human cells to pluripotency using mature microRNAs. *Cell Stem Cell* 2011;8:633–638.
- Hou P, Li Y, Zhang X, *et al*. Pluripotent stem cells induced from mouse somatic cells by small-molecule compounds. *Science* 2013;341:651–654.
- Gore A, Li Z, Fung HL, *et al*. Somatic coding mutations in human induced pluripotent stem cells. *Nature* 2011;471:63–67.
- Toyoda M, Yamazaki-Inoue M, Itakura Y, *et al*. Lectin microarray analysis of pluripotent and multipotent stem cells. *Genes Cells* 2011;16:1–11.

37. Nishino K, Toyoda M, Yamazaki-Inoue M, *et al.* Defining hypomethylated regions of stem cell-specific promoters in human iPSCs derived from extra-embryonic amnions and lung fibroblasts. *PLoS One* 2010;5:e13017.
38. Park IH, Zhao R, West JA, *et al.* Reprogramming of human somatic cells to pluripotency with defined factors. *Nature* 2008;451:141–146.
39. Hannan NR, Segeritz CP, Touboul T, *et al.* Production of hepatocyte-like cells from human pluripotent stem cells. *Nat Protoc* 2013;8:430–437.
40. Vallier L, Touboul T, Brown S, *et al.* Signaling pathways controlling pluripotency and early cell fate decisions of human induced pluripotent stem cells. *Stem Cells* 2009;27:2655–2666.
41. Pick M, Ronen D, Yanuka O, *et al.* Reprogramming of the MHC-I and its regulation by NFκB in human-induced pluripotent stem cells. *Stem Cells* 2012;30:2700–2708.
42. Marchand M, Anderson EK, Phadnis SM, *et al.* Concurrent generation of functional smooth muscle and endothelial cells via a vascular progenitor. *Stem Cells Transl Med* 2014;3:91–97.
43. Uosaki H, Fukushima H, Takeuchi A, *et al.* Efficient and scalable purification of cardiomyocytes from human embryonic and induced pluripotent stem cells by VCAM1 surface expression. *PLoS One* 2011;6:e23657.
44. Choi KD, Yu J, Smuga-Otto K, *et al.* Hematopoietic and endothelial differentiation of human induced pluripotent stem cells. *Stem Cells* 2009;27:559–567.
45. Cai J, DeLaForest A, Fisher J, *et al.* Protocol for directed differentiation of human pluripotent stem cells toward a hepatocyte fate. In: *StemBook(Internet)* 10 Jun 2012. Available from <http://www.ncbi.nlm.nih.gov/books/NBK133278>.
46. Chambers SM, Fasano CA, Papapetrou EP, *et al.* Highly efficient neural conversion of human ES and iPSCs by dual inhibition of SMAD signaling. *Nat Biotechnol* 2009;27:275–280.
47. Lee G, Chambers SM, Tomishima MJ, *et al.* Derivation of neural crest cells from human pluripotent stem cells. *Nat Protoc* 2010;5:688–701.
48. Kriks S, Shim JW, Piao J, *et al.* Dopamine neurons derived from human ES cells efficiently engraft in animal models of Parkinson's disease. *Nature* 2011;480:547–551.
49. Di Giorgio FP, Boulting GL, Bobrowicz S, *et al.* Human embryonic stem cell-derived motor neurons are sensitive to the toxic effect of glial cells carrying an ALS-causing mutation. *Cell Stem Cell* 2008;3:637–648.
50. Lancaster MA, Renner M, Martin CA, *et al.* Cerebral organoids model human brain development and microcephaly. *Nature* 2013;501:373–379.
51. Nakano T, Ando S, Takata N, *et al.* Self-formation of optic cups and storable stratified neural retina from human ESCs. *Cell Stem Cell* 2012;10:771–785.
52. Suga H, Kadoshima T, Minaguchi M, *et al.* Self-formation of functional adenohypophysis in three-dimensional culture. *Nature* 2011;480:57–62.
53. Takebe T, Sekine K, Enomura M, *et al.* Vascularized and functional human liver from an iPSC-derived organ bud transplant. *Nature* 2013;499:481–484.
54. Melton DA. Using stem cells to study and possibly treat type 1 diabetes. *Philos Trans R Soc Lond B Biol Sci* 2011;366:2307–2311.
55. Matsunari H, Nagashima H, Watanabe M, *et al.* Blastocyst complementation generates exogenic pancreas *in vivo* in apneurogenic cloned pigs. *Proc Natl Acad Sci USA* 2013;110:4557–4562.
56. Mahfouz MM, Li L, Shamimuzzaman M, *et al.* *De novo*-engineered transcription activator-like effector (TALE) hybrid nuclease with novel DNA binding specificity creates double-strand breaks. *Proc Natl Acad Sci USA* 2011;108:2623–2628.
57. Christian M, Cermak T, Doyle EL, *et al.* Targeting DNA double-strand breaks with TAL effector nucleases. *Genetics* 2010;186:757–761.
58. Hockemeyer D, Wang H, Kiani S, *et al.* Genetic engineering of human pluripotent cells using TALE nucleases. *Nat Biotechnol* 2011;29:731–734.
59. Tesson L, Usal C, Ménoret S, *et al.* Knockout rats generated by embryo microinjection of TALENs. *Nat Biotechnol* 2011;29:695–696.
60. Sander JD, Cade L, Khayter C, *et al.* Targeted gene disruption in somatic zebrafish cells using engineered TALENs. *Nat Biotechnol* 2011;29:697–698.
61. Sung YH, Baek JJ, Kim DH, *et al.* Knockout mice created by TALEN-mediated gene targeting. *Nat Biotechnol* 2013;31:23–24.
62. Pennisi E. The tale of the TALEs. *Science* 2012;338:1408–1411.
63. Ochiai H, Miyamoto T, Kanai A, *et al.* TALEN-mediated single-base-pair editing identification of an intergenic mutation upstream of BUB1B as causative of PCS (MVA) syndrome. *Proc Natl Acad Sci USA* 2014;111:1461–1466.
64. Bacman SR, Williams SL, Pinto M, *et al.* Specific elimination of mutant mitochondrial genomes in patient-derived cells by mitoTALENs. *Nat Med* 2013;19:1111–1113.
65. Kim Y, Kweon J, Kim A, *et al.* A library of TAL effector nucleases spanning the human genome. *Nat Biotechnol* 2013;31:251–258.
66. Liu J, Gaj T, Patterson JT, *et al.* Cell-penetrating peptide-mediated delivery of TALEN proteins via bioconjugation for genome engineering. *PLoS One* 2014;9:e85755.
67. Jia J, Jin Y, Bian T, *et al.* Bacterial delivery of TALEN proteins for human genome editing. *PLoS One* 2014;9:e91547.
68. Cong L, Ran FA, Cox D, *et al.* Multiplex genome engineering using CRISPR/Cas systems. *Science* 2013;339:819–823.
69. Mali P, Yang L, Esvelt KM, *et al.* RNA-guided human genome engineering via Cas9. *Science* 2013;339:823–826.
70. Jinek M, East A, Cheng A, *et al.* RNA-programmed genome editing in human cells. *Elife* 2013;2:e00471.
71. Cho SW, Kim S, Kim JM, *et al.* Targeted genome engineering in human cells with the Cas9 RNA-guided endonuclease. *Nat Biotechnol* 2013;31:230–232.
72. Hwang WY, Fu Y, Reyon D, *et al.* Efficient genome editing in zebrafish using a CRISPR-Cas system. *Nat Biotechnol* 2013;31:227–229.
73. Wang H, Yang H, Shivalila CS, *et al.* One-step generation of mice carrying mutations in multiple genes by CRISPR/Cas-mediated genome engineering. *Cell* 2013;153:910–918.
74. Wu Y, Liang D, Wang Y, *et al.* Correction of a genetic disease in mouse via use of CRISPR-Cas9. *Cell Stem Cell* 2013;13:659–662.
75. Shalem O, Sanjana NE, Hartenian E, *et al.* Genome-scale CRISPR-Cas9 knockout screening in human cells. *Science* 2014;343:84–87.
76. Wang T, Wei JJ, Sabatini DM, *et al.* Genetic screens in human cells using the CRISPR-Cas9 system. *Science* 2014;343:80–84.
77. Yin H, Xue W, Chen S, *et al.* Genome editing with Cas9 in adult mice corrects a disease mutation and phenotype. *Nat Biotechnol* 2014;32:551–553.
78. Chen B, Gilbert LA, Cimini BA, *et al.* Dynamic imaging of genomic loci in living human cells by an optimized CRISPR/Cas system. *Cell* 2013;155:1479–1491.
79. Qi LS, Larson MH, Gilbert LA, *et al.* Repurposing CRISPR as an RNA-guided platform for sequence-specific control of gene expression. *Cell* 2013;152:1173–1183.
80. Kearns NA, Genga RM, Enuameh MS, *et al.* Cas9 effector-mediated regulation of transcription and differentiation in human pluripotent stem cells. *Development* 2014;141:219–223.