

Comparison of sample preparation methods for ChIP-chip assays

Henriette O'Geen¹, Charles M. Nicolet¹, Kim Blahnik¹, Roland Green², and Peggy J. Farnham¹

¹University of California-Davis, Davis, CA and ²NimbleGen Systems Inc., Madison, WI, USA

BioTechniques 41:577-580 (November 2006)
doi 10.2144/000112268

A single chromatin immunoprecipitation (ChIP) sample does not provide enough DNA for hybridization to a genomic tiling array. A commonly used technique for amplifying the DNA obtained from ChIP assays is ligation-mediated PCR (LM-PCR). However, using this amplification method, we could not identify Oct4 binding sites on genomic tiling arrays representing 1% of the human genome (ENCODE arrays). In contrast, hybridization of a pool of 10 ChIP samples to the arrays produced reproducible binding patterns and low background signals. However, the pooling method would greatly increase the number of ChIP reactions needed to analyze the entire human genome. Therefore, we have adapted the GenomePlex® whole genome amplification (WGA) method for use in ChIP-chip assays; detailed ChIP and amplification protocols used for these analyses are provided as supplementary material. When applied to ENCODE arrays, the products prepared using this new method resulted in an Oct4 binding pattern similar to that from the pooled Oct4 ChIP samples. Importantly, the signal-to-noise ratio using the GenomePlex WGA method is superior to the LM-PCR amplification method.

INTRODUCTION

The technique of chromatin immunoprecipitation (ChIP) has proven to be a powerful tool, allowing the detection of protein-DNA interactions in living cells. Although this technique was first adapted for use with mammalian cells less than 10 years ago (1,2), it is now the gold standard experiment for the identification of a target gene of a particular transcription factor. Over the last several years, great strides have been made in expanding the use of ChIP from a one gene-at-a-time approach to a global analysis tool through the hybridization of the samples to genomic microarrays (i.e., the ChIP-chip assay). Today, arrays representing promoter regions (3), CpG islands (4–6), or entire genomes (7) are used in combination with ChIP to identify binding sites for transcription factors and components of the transcriptional machinery and to define chromatin structure. However, a single ChIP sample does not provide enough DNA for labeling and hybridization to an array. A commonly used technique for amplifying the DNA obtained from

ChIP assays is ligation-mediated PCR (LM-PCR). Unfortunately, we have found that this method often produces very high background when samples are analyzed on genomic tiling arrays. In this study, we have compared three ChIP sample preparation methods that differ in the background noise and reproducibility of binding site identification.

MATERIALS AND METHODS

Cell Culture

Ntera2 cells were grown in Dulbecco's modified Eagle's medium (DMEM) supplemented with 2 mM glutamine, 100 U/mL of penicillin and streptomycin, and 10% fetal bovine serum (FBS). All cells were incubated at 37°C in a humidified 5% CO₂ incubator.

ChIP-Chip Assays

ChIP assays (1 × 10⁷ cells/assay) were performed following the protocol

provided in the supplementary materials (available online at www.BioTechniques.com with updates at genomics.ucdavis.edu/farnham and genomecenter.ucdavis.edu/expression_analysis). The Oct4 antibody used in this study was purchased from Santa Cruz Biotechnology (Santa Cruz, CA, USA), and the rabbit anti-goat immunoglobulin G (IgG) was purchased from MP Biomedicals (Solon, OH, USA). For PCR analysis of the ChIP samples prior to product generation, QIAquick®-purified immunoprecipitates (Qiagen, Valencia, CA, USA) were dissolved in 50 µL water. Standard PCRs using 2 µL immunoprecipitated DNA were performed. PCR products were separated by electrophoresis through 1.5% agarose gels and visualized using ethidium bromide.

Three different preparation methods were used to obtain enough ChIP DNA for application to genomic microarrays. ChIP-chip experiments were performed using two independent cultures of cross-linked Ntera2 cells for each method.

Method 1. LM-PCR. For this method, one half of a ChIP sample (from 1 × 10⁷ cells) was used for linker ligation. Amplification of the linker-ligated DNA using LM-PCR is described in detail at genomics.ucdavis.edu/farnham; see also Reference 8.

Method 2. Pooling ChIP samples. For this method, 10 individual Oct4 ChIP assays were performed from each of two sets of 1 × 10⁸ cross-linked cells (1 × 10⁷ cells/ChIP assay). ChIP samples were processed separately following the standard protocol, except that after pre-clearing the chromatin with StaphA cells, all 10 ChIP samples were pooled into one tube for the washing steps. Washes and elution of the pooled ChIPs were then carried out as described in the standard protocol.

Method 3. Whole genome amplification (WGA). An adaptation of the standard protocol for WGA using the GenomePlex® WGA kit (Sigma-Aldrich, St. Louis, MO, USA) was used. Briefly, the initial random fragmentation step was eliminated, and an entire ChIP sample (from 1 × 10⁷ cells) or 10 ng input chromatin were amplified. This usually provides enough sample for one array. However,

if additional product is needed, then a second round of amplification (using 10–20 ng of the first amplification sample) can be performed. A detailed protocol for the WGA method is provided in the supplementary materials.

Biological replicates of LM-PCR products, pooled ChIP samples, and WGA products (a total of six samples) were applied to ENCODE (Encyclopedia of DNA Elements) oligonucleotide arrays (NimbleGen Systems, Madison, WI, USA) containing approximately 380,000 50-mer probes per array, tiled every 38 bp. The regions included on the arrays encompassed the 30 Mb of the repeat masked ENCODE sequences, representing approximately 1% of the human genome. The labeling of DNA samples for ChIP-chip analysis was performed by NimbleGen Systems, Inc. Briefly, each DNA sample (1 μ g) was denatured in the presence of 5' CyTM3- or Cy5-labeled random nonamers (TriLink Biotechnologies, San Diego, CA, USA) and incubated with 100 U (exo-) Klenow fragment (New England Biolabs, Ipswich, MA, USA) and dNTP mixture [6 mM each in TE buffer (10 mM Tris, 1 mM EDTA, pH 7.4; Invitrogen, Carlsbad, CA, USA)] for 2 h at 37°C. Reactions were terminated by addition of 0.5 M EDTA, pH 8.0, precipitated with isopropanol, and resuspended in water. Then, 13 μ g Cy5-labeled ChIP sample and 13 μ g Cy3-labeled total sample were mixed, dried

down, and resuspended in 40 μ L hybridization buffer (NimbleGen Systems) plus 1.5 μ g human COT1 DNA. After denaturation, hybridization was carried out in a MAUI[®] (MicroArray User Interface) Hybridization System (BioMicro Systems, Salt Lake City, UT, USA) for 18 h at 42°C at the NimbleGen Service Laboratory. The arrays were washed using wash buffer system (NimbleGen Systems), dried by centrifugation, and scanned at 5 μ m resolution using the GenePix[®] 4000B scanner (Axon Instruments, Union City, CA, USA). Fluorescence intensity raw data were obtained from scanned images of the oligonucleotide tiling arrays using NimbleScan[™] 2.0 extraction software (NimbleGen Systems). For each spot on the array, log₂-ratios of the Cy5-labeled test sample versus the Cy3-labeled reference sample were calculated. Then, the biweight mean of this log₂ ratio was subtracted from each point; this procedure is approximately equivalent to mean-normalization of each channel. Sites bound by Oct4 were identified using the peak calling algorithm described in Bieda et al. (9), with minor modifications (available upon request). The peaks called for both biological replicates of the LM-PCR, pooling, and WGA methods are provided as supplementary material. The array data has been deposited into

Table 1. Comparison of Sample Preparation Methods

Method	Total Peaks ^a	Overlapping ^b	Overlap (%)
LM-PCR	543	82	15
Pooled	491	343	70
WGA	449	280	63

LM-PCR, ligation-mediated PCR; WGA, whole genome amplification.
^aTotal number of peaks called on both arrays.
^bIf at least one of the ends of a peak region from one array overlapped a peak region from the other array, the peaks were considered to be overlapping.

Gene Expression Omnibus (GEO; series GSE5251).

RESULTS AND DISCUSSION

To identify Oct4 binding sites in the human genome, we first performed a ChIP experiment using an antibody to Oct4 and demonstrated that the Oct4 ChIP sample showed enrichment when primers specific to the NANOG and EVX1 promoters (known Oct4 binding sites) were used in PCRs, but no enrichment when negative control primers specific for the *DHFR* gene were used (data not shown). We then used LM-PCR to amplify the Oct4 ChIP samples and hybridized the amplified samples to ENCODE arrays. Using ChIP samples amplified by LM-PCR, we have previously identified binding sites for E2F family members using CpG island (4), promoter (9,10), and genomic tiling (9) arrays. However, using the LM-PCR amplification method, we found that Oct4 binding sites could not be distinguished from the background noise on the arrays (Figure 1, top panel). For example, although the Oct4 binding site in the EVX1 promoter is present on the array used in this study, it could not be identified above background noise. Also, two Oct4 binding sites (confirmed by PCR analysis of ChIP samples) within the *EXT1* gene, indicated with arrows in Figure 1, do not show enhanced enrichment as compared with the surrounding DNA. Peak prediction analysis of two biologically independent ChIP-chip assays performed using the LM-PCR method was carried out using a 98th percentile threshold of log₂ oligomer ratios and a *P* value *P* < 0.0001 (9). Although

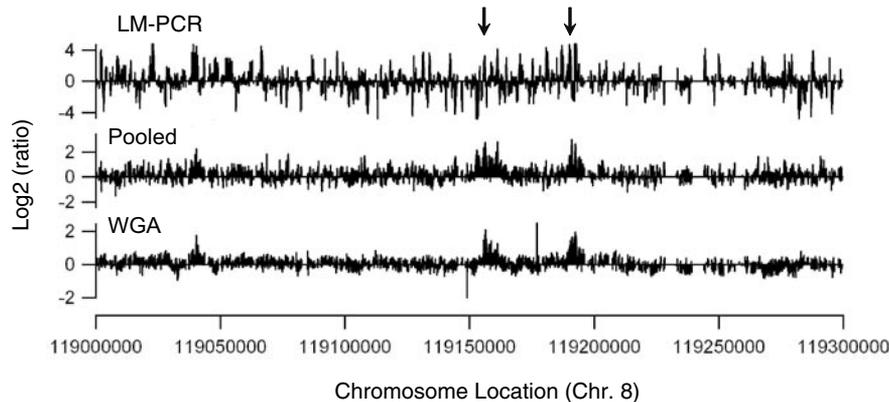


Figure 1. Comparison of three different sample preparation methods for ChIP-chip assays. The hybridization profile of a 300-kb region of chromosome 8 surrounding the *EXT1* gene is shown for samples prepared by the LM-PCR (top panel), pooled (middle panel), or WGA (bottom panel) methods. Oct4 binding sites confirmed by PCR are indicated with arrows. ChIP, chromatin immunoprecipitation; LM-PCR, ligation-mediated PCR; WGA, whole genome amplification.

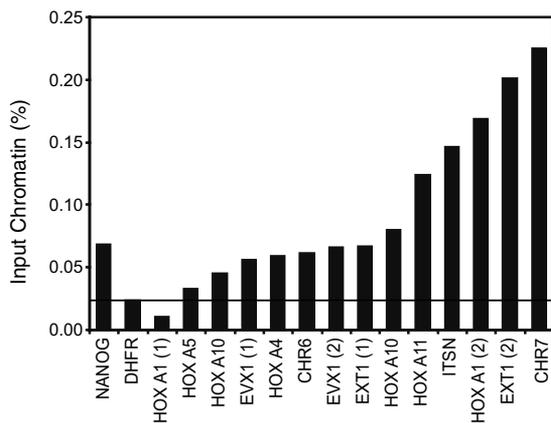


Figure 2. The results of PCR assays (using an independent ChIP sample) for 14 Oct4 binding sites predicted from the WGA array data are shown. Two different binding sites were assayed for the *HoxA1*, *EVX1*, and *EXT1* genes. Primers specific to the NANOG promoter were used as a positive control, and primers specific to the *DHFR* gene were used as a negative control. Enrichments above the negative control are considered confirmed Oct4 binding sites. ChIP, chromatin immunoprecipitation; WGA, whole genome amplification.

hundreds of peaks were called for the two arrays using the LM-PCR-derived products, very few peaks were in common on both arrays (Table 1 and supplementary material).

Because known Oct4 binding sites were enriched in the ChIP samples, it was likely that the inability to identify binding sites on the arrays was a result of the amplification method and not inefficient immunoprecipitation. To test this hypothesis, we performed 10 ChIP reactions for each of two biologically independent samples of cross-linked cells. The 10 ChIP samples from a given batch of cells were pooled, and the two pools were applied separately to genomic tiling arrays. We found that the pooling method greatly reduced the background noise on the array and produced reproducible binding patterns (Figure 1, middle panel). In fact, approximately 70% of the peaks identified on one array were identified on the biological replicate array (Table 1 and supplementary material).

Unfortunately, pooling ChIP samples is not always possible (e.g., if using specialized cell types or tumor tissues), and the need to pool 10 ChIP samples for every array would greatly increase the number of ChIP reactions needed to analyze the entire human genome. Therefore, we felt that a different method for amplifying ChIP samples was required. The method of WGA has proven very useful for investigators performing comparative genomic hybridizations (see www.sigmaaldrich.com/sigma/bulletin/wga1bul.pdf). The standard protocol for this technique is to first use a random chemical fragmen-

tation of the genome, producing a series of overlapping short templates averaging 400 bp. Next, the DNA fragments are efficiently primed to generate a library of DNA fragments with defined 3' and 5' termini. This library is then replicated using linear amplification in the initial stages, followed by a limited round of geometric amplifications. Because ChIP samples are obtained using sonicated chromatin that has an average size of 500 bp to 1 kb, we reasoned that the chemical fragmentation step should not be necessary. Therefore, we used an entire ChIP sample (obtained from 1×10^7 cells) for the library generation and subsequent amplification. Using this protocol, we found that the predicted Oct4 peaks show a very similar pattern as in the pooled ChIP samples, and the background noise was very low (Figure 1, bottom panel). Using the WGA method, we found that approximately 63% of the peaks were detected on both arrays (Table 1 and supplementary material). These results are very similar to those obtained by analysis of the arrays hybridized with the pooled samples. One reason why the overlap percentage was not higher than 63%–70% when the pooled and WGA samples were analyzed is due to limitations of the peak-calling program. As shown in Supplementary Figure S1, very similar binding patterns of Oct4 on two arrays can lead to differences in the number and exact positions of called peaks.

The Oct4 binding sites identified using the WGA method were tested by standard PCR analyses using a ChIP sample from a third independent culture

of cells (Figure 2). After analyzing 14 predicted Oct4 binding sites, we obtained a 93% confirmation rate, indicating that the WGA amplification method results in an accurate representation of a ChIP sample obtained from a small number of cells.

Conclusions

We have shown that the method of LM-PCR-mediated amplification does not work well for all ChIP samples, perhaps dependent upon the number of binding sites and the abundance of the factor. We have tested a different amplification method, originally developed to provide accurate representation of the genome for studies of copy number changes and SNP analyses in tumor samples. We found that the signal-to-noise ratio obtained from the hybridization of the WGA products to genomic arrays is superior to the LM-PCR method of amplification for ChIP samples, not only for Oct4, but also for a number of other human and mouse transcription factors (data not shown). Based on the low background, reproducibility, and the fact that a single ChIP sample provides sufficient material for several array hybridizations, we recommend the WGA protocol for ChIP-chip analyses.

ACKNOWLEDGMENTS

This work was supported in part by Public Health Service grant nos. CA45250, HG003129, DK067889, and UCD FL69920. We thank the members of the Farnham lab for helpful discussion and data analysis and Heather Witt for preparation of the modified ChIP protocol.

COMPETING INTERESTS STATEMENT

R.G. is an employee of NimbleGen Systems Inc. Arrays from this company were used in the ChIP-chip studies. The other authors declare no competing interests.

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Received 3 July 2006; accepted 4 August 2006.

Address correspondence to Peggy Farnham, Genome and Biomedical Sciences Facility, One Shields Avenue, University of California-Davis, Davis, CA 95616, USA. e-mail: pjfarnham@ucdavis.edu

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