the *TP53*, *CDKN2A*, *RB1*, or *RAS* genes (Ahuja et al., 1989; Kelman et al., 1989; LeMaistre et al., 1989; Feinstein et al., 1991; Nakai et al., 1992, 1994; Mitani et al., 1994; Nakai and Misawa, 1995; Sill et al., 1995; Nakamura et al., 1996; Fioretos et al., 1999; Beck et al., 2000). However, the molecular mechanisms responsible for disease progression in CML have not been fully understood. Array-based comparative genomic hybridization (array CGH) is a robust technology in which a large number of genomic clones are spotted on a glass slide and comparatively hybridized to differentially labeled tumor and reference DNA to enable high-resolution analysis of copy number changes in cancer genomes (Pinkel et al., 1998). Although the array CGH technique has been drawing increasing attention as a tool for studying alterations of genomes in various tumors (Albertson and Pinkel, 2003), it had not been applied to the analysis of patients with CML.

In the present study, to identify genes underlying stage progression in CML, we manufactured Human 1M arrays containing 3,151 bacterial artificial chromosome (BAC) DNAs and performed CGH analysis in 55 primary CML samples in different stages using these arrays. A number of previously unrecognized small cryptic genomic regions were identified.

MATERIALS AND METHODS

PATIENTS AND SAMPLES

After obtaining informed consent, bone marrow or peripheral-blood samples were obtained from 55 Japanese patients diagnosed with CML. Twenty-five of the patients were in the CP stage, 4 were in the AP stage, and 26 were in the BC stage. Clinical details are summarized in Table 1. After approval by the ethical committee at the University of Tokyo, all the samples were subjected to extraction of genomic DNA and anonymized to be used for further analysis according to the regulation of the Japanese government.

Array Fabrication

We constructed Human 1M arrays containing a subset of the FISH (fluorescence in situ hybridization) Mapped Clones V1.3 collection, which were obtained from BACPAC Resources Center (Children's Hospital Oakland Research Institute, Oakland, CA). After excluding clones missing mapping information, a total of 3,151 clones were finally selected for fabrication of Human 1M arrays (Supplementary Table 1; Supplementary material for this article can be found at http://www.interscience.wiley.com/jpages/1045-2257/suppmat), which could be used for genomewide copy number detection at an average resolution of approximately 1.0 Mb. Each BAC DNA was amplified with degenerated oligonucleotide-primed PCR (DOP-PCR) according to the protocol published by Fiegler et al. (2003), with the minor modification of an equimolar combination of DOP 1, 2, and 3 primers being used in the first PCR cycles. Amplified DNA was spotted in duplicate onto GAPS™ II coated slides (Corning, International K.K., Tokyo, Japan), using an Affymetrix 419 Arrayer (Affymetrix, Santa Clara, CA). Before hybridization, array slides were briefly rehydrated over steam and immediately dried on a 75°C heat block. After being baked in a drying oven at 65°C for 3 h and UV-crosslinked at 60 mJ, the slides were rinsed with 0.2× standard saline citrate (SSC) and then with distilled water. The reactive moieties of amino-silane remaining on the glass surface were inactivated for 20 min by gently shaking arrays in a blocking solution, which was freshly prepared by dissolving 4.15 g of succinic anhydride in 245 ml of 1-methyl-2-pyrrolidinone and then adding 22.5 ml of sodium borate (1M, pH 8.0). The slides were briefly rinsed with distilled water and preserved in a desiccator at room temperature, and immediately before hybridization, they were treated in boiling water for 2 min, placed in 100% cold ethanol, and then dried by centrifugation.

DNA Labeling and Hybridization to BAC Arrays

Genomic DNA was extracted from mononuclear cells of the bone marrow or peripheral blood of normal individuals using a PUREGENE™ DNA Isolation Kit (Gentra Systems, Minneapolis, MN). One microgram each of normal reference genomic (male or female) and test DNA were labeled with Cy3-dUTP and Cy5-dUTP, respectively, using a BioPrime® Array CGH Genomic Labeling System (Invitrogen, Carlsbad, CA). After overnight incubation at 37°C, unincorporated nucleotides were removed by use of a BioPrime™ Array CGH Purification Module (Invitrogen, Carlsbad, CA). The labeled test and reference DNA were ethanol-precipitated together with 80 μg of human Cot-1 DNA (Invitrogen, Carlsbad, CA) and 100 μg of yeast tRNA (Roche, Basel, Switzerland), redissolved in a hybridization mix [50% formamide, 5% dextran sulfate, 2× SSC, 5% Tris (pH 7.4), 0.1% Tween 20], and denatured at 75°C for 15 min. After incubation at 37°C for 30 min, the mixture was

TABLE 1. Patient Characteristics, Cytogenetic Description of Their Karyotypes, and Presence of *BCR/ABL* Confirmed by FISH or RT-PCR

Case No.	Sex	Age	Stage	Phenotype	Blast(%)	Karyotype	Methods of *BCR/ABL* detection
AP1	M	51	CML AP		6	46,XY,t(9;22)(q34;q11)(20/20)	NS
AP2	F	56	CML AP		2	50,XX,t(9;22)(q34;q11)+13, +19,+21,+22(8/15) 51,XX,t(9;22)(q34;q11), +t(9;22),+13,+19,+21, +22(4/15) 52,XX,+8,t(9;22)(q34;q11), +t(9;22),+13,+19,+21, +22(2/15) 47,XX,t(9;22)(q34;q11), +19,−20,−21,+der(22) t(9;22),+mar(1/15)	FISH and RT-PCR
AP3	M	37	CML AP		3.3	46,XY,t(9;22)(q34;q11)(18/20) 47,XY,+8,t(9;22)(q34;q11) (2/20)	RT-PCR
AP4	M	74	CML AP		9	46,XY,t(9;22)(q34;q11)(14/20) 45,XY,−21,t(9;22)(q34;q11) (5/20) 45,XY,−17,t(9;22)(q34;q11) (1/20)	RT-PCR
BC1	M	78	CML BC	ND	30	46,XY,t(9;22)(q34;q11)	NS
BC2	M		CML BC	ND	72	46,XY,t(9;22)(q34;q12)	NS
BC3	M	65	CML BC	lymphoid	90	46,XY,t(9;22)(q34;q11)	NS
BC4	M	33	CML BC	lymphoid	70	NA	NS
BC5	M		CML BC	lymphoid	65	NA	NS
BC6	F	48	CML BC	lymphoid	56	46,XX,t(9;22)(q34;q11)	NS
BC7	F	42	CML BC	lymphoid	60	46,XX,t(9;22)(q34;q11)	NS
BC8	F	42	CML BC	lymphoid	70	46,XX,t(9;22)(q34;q11)	NS
BC9	F	60	CML BC	myeloid	98	46,XX,t(9;22)(q34;q11)	NS
BC10	M	62	CML BC	myeloid	90	46,XY,t(9;22)(q34;q11)	NS
BC11	F		CML BC	myeloid	60	NA	NS
BC12	F	53	CML BC	myeloid	20	NA	NS
BC13	F		CML BC	myeloid	88	NA	NS
BC14	M		CML BC	myeloid	75	NA	NS
BC15	M	46	CML BC	myeloid	70	46,XY,t(9;22)(q34;q11)	NS
BC16	M	67	CML BC	myeloid	73	48,XY,t(3;21;18)(q21;q22;p11), +8,t(9;22)(q34;q11), +12(20/20)	FISH and RT-PCR
BC17	F	57	CML BC	myeloid	39	46,XY,t(9;22)(q34;q11)(10/10)	NS
BC18	M	51	CML BC	myeloid	86	46,XY,t(9;22)(q34;q11)(20/20)	FISH and RT-PCR

(Continued)

TABLE 1. Patient Characteristics, Cytogenetic Description of Their Karyotypes, and Presence of BCR/ABL Confirmed by FISH or RT-PCR (Continued)

Case No.	Sex	Age	Stage	Phenotype	Blast(%)	Karyotype	Methods of *BCR/ABL* detection
BC19	M	54	CML BC	myeloid	13	NA	FISH and RT-PCR
BC20	M	69	CML BC	myeloid	35	46,XY,t(9;22)(q34;q11)(13/20) 46,XY,t(9;22)(q34;q11),der(12)t(1;12)(q12;q24)(3/20) 46,XY,t(9;22)(q34;q11),der(19)t(1;19)(q12;p13)(4/20)	FISH and RT-PCR
BC21	M	71	CML BC	lymphoid	59	48,XY,11q+,+19,22q−,+22q−(20/20)	RT-PCR
BC22	M	62	CML BC	myeloid	61	46,XY,t(20;22)(p13;q11)(8/20) 47,XY,t(20;22)(p13;q11),+der(22)t(20;22)(p13;q11)(5/20) 45,XY,del(4)(q31),add(6)(p21),der(8;17)(q10;q10),+i(8)(q10),+add(9)(p22),−13,−16,t(20;22)(p13;q11),der(22)t(20;22),inc(1/20) 44,X,−Y,add(6)(p21),der(8;17)(q10;q10),+i(8)(q10),add(9)(p22),−13,−16,t(20;22)(p13;q11),inc(1/20) 74–87, ND, including add(6)(p21),der(8;17)(q10;q10),add(9)(p22),t(20;22)(p13;q11)(5/20)	RT-PCR
BC23	M	28	CML BC	myeloid	36	46,XY,t(9;22)(q34;q11)(18/20) 46,XY(2/20)	FISH and RT-PCR
BC24	M	60	CML BC	myeloid	44	48,XY,+8,t(9;22)(q34;q11),+der(22)t(9;22)(q34;q11)(19/20) 50,XY,+8,+8,t(9;22)(q34;q11),+21,+der(22)t(9;22)(q34;q11)(1/20)	FISH and RT-PCR
BC25	M	37	CML BC	myeloid	28	46,XY,t(9;22)(q34;q11)(12/20) 46,XY(8/20)	FISH and RT-PCR
BC26	M	64	CML BC	myeloid	85	45,XY,add(5)(q15),der(9)t(9;22)(q34;q11),add(12)(p11),del(17)(p11),add(19)(q13),−21,der(22)add(22)(p11)t(9;22)(17/20)	FISH and RT-PCR

(Continued)

TABLE 1. Patient Characteristics, Cytogenetic Description of Their Karyotypes, and Presence of *BCR/ABL* Confirmed by FISH or RT-PCR (Continued)

Case No.	Sex	Age	Stage	Phenotype	Blast(%)	Karyotype	Methods of *BCR/ABL* detection
						45,XY,der(5)t(5;21)(q31;q11), der(9)t(9;22)(q34;q11), del(17)(p11),add(19)(q13), −21,der(22)add(22)(p11) t(9;22)(1/20)	
						48,XY,dup(3)(q21q27),add(4) (q21),der(5)t(5;21)(q31;q11), t(9;22)(q34;q11),add(13)(p11), del(17)(p11),+19,−21, +der(22)t(9;22),+mar(1/20)	
						48,XY,dup(3)(q21q27),−4, der(5)t(5;21)(q31;q11), t(9;22)(q34;q11),add(13)(p11), del(17)(p11),+19,−21, +der(22)t(9;22),+mar(1/20)	
CP1	M	40	CML CP		0	46,XY,t(9;22)(q34;q11)	NS
CP2	M	28	CML CP		0	NA	NS
CP3	F	60	CML CP		0	46,XX,t(9;22)(q34;q11)	NS
CP4	M	62	CML CP		0	46,XY,t(9;22)(q34;q11)	NS
CP5	M	38	CML CP		5	46,XY,t(9;22)(q34;q11)	NS
CP6	M	35	CML CP		5	46,XY,t(9;22)(q34;q11)	NS
CP7	M	54	CML CP		0	46,XY,t(9;22)(q34;q11)	NS
CP8	F		CML CP		0	NA	NS
CP9	M		CML CP		0	46,XY,t(9;22)(q34;q11)	NS
CP10	M		CML CP		1	46,XY,t(9;22)(q34;q11)	NS
CP11	F	32	CML CP		0	46,XX,t(9;22)(q34;q11)	NS
CP12	F	59	CML CP		0	46,XX,t(9;22)(q34;q11)	NS
CP13	M	51	CML CP		0	46,XY,t(9;22)(q34;q11)	NS
CP14	F		CML CP		0	46,XX,t(9;22)(q34;q11)	NS
CP15	M	46	CML CP		0	46,XY,t(9;22)(q34;q11)	NS
CP16	M	58	CML CP		0	46,XY,t(9;22)(q34;q11)	NS
CP17	F	58	CML CP		0	46,XX,t(9;22)(q34;q11)	NS
CP18	F	74	CML CP		0	46,XX,t(9;22)(q34;q11)	NS
CP19	F	54	CML CP		0	46,XX,t(9;22)(q34;q11)	NS
CP20	M		CML CP		0.5	46,XY,t(9;22)(q34;q11)	NS
CP21	M	71	CML CP		0	46,XY,t(9;22)(q34;q11)(20/20)	NS
CP22	M	40	CML CP		0	46,XY,t(9;22)(q34;q11)(20/20)	FISH and RT-PCR
CP23	M	43	CML CP		1.5	46,XY(20/20)	FISH and RT-PCR
CP24	F	55	CML CP		2	46,XX,t(9;22)(q34;q11)(20/20)	NS
CP25	M	75	CML CP		0	46,XY,t(9;22)(q34;q11)	NS

ND: not determined; NA: information not available; NE: not examined; NS: not specified in clinical records; Ph chr: Philadelphia chromosome; chr: chromosome; RT-PCR: reverse-transcriptase-polymerase-chain-reaction; The t(20;22)(p13;q11) in case BC26 is a variant Ph translocation.

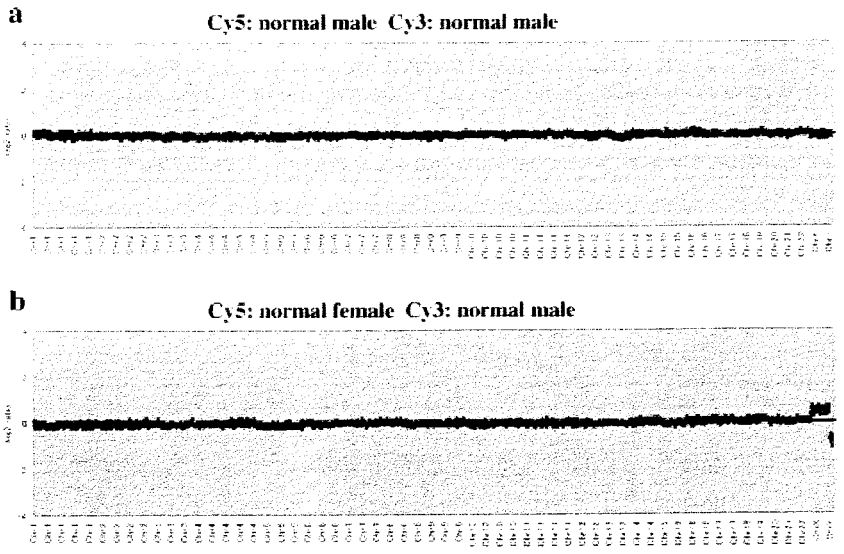

Figure 1. Representative array CGH results obtained from reference-versus-reference control hybridization. Clones are ordered from chromosomes 1 to 22, X, and Y and within each chromosome according to the UCSC mapping position (http://genome.ucsc.edu/; May 2004 draft). Each spot represents an average $\log_2$ signal ratio for each BAC locus. (a) For all loci, $\log_2$ ratios were within the thresholds −0.2 and 0.2 in the male-versus-male control experiment. (b) Gain in chromosome X (0.435 ± 0.124) and loss in chromosome Y (−0.807 ± 0.167) were clearly visualized in the female-versus-male control experiment (Cy5 and Cy3, respectively).

applied to an array slide placed in a MAUI® Mixer AO Hybridization Chamber Lid (BioMicro Systems, Salt Lake City, UT) and incubated at 37°C for 60–66 h using a MAUI Hybridization System (BioMicro Systems). After hybridization, the slides were washed once in a solution of 50% formamide and 2× SSC for 15 min at 50°C and once in 2× SSC for 15 min at room temperature. Slides were rinsed briefly with 0.2× SSC and dried immediately by centrifugation.

Image Analysis and Processing

After hybridization, the arrays were scanned by an Affymetrix 428™ Array Scanner (Affymetrix, Santa Clara, CA). The scanned image was analyzed by an ImaGene v4.2 (BioDiscovery, Inc., Marina Del Rey, CA) in order to extract Cy3 and Cy5 signals for each spot, and after local background signals were subtracted, test/reference $\log_2$ ratios of the test and reference signals were calculated for all spots. The $\log_2$ ratios were normalized so that the average $\log_2$ ratio of all spots became zero. A spot was eliminated from the analysis if the signal intensity after the background subtraction in either Cy5 or Cy3 was less than −18 decibels or the duplicated signals differed by more than 0.4 in the $\log_2$ ratios. The average $\log_2$ ratios of the two replicate spots were calculated for the remaining spots. An experiment was not adopted if less than 90% of all spots met the above-mentioned criteria or if the standard deviation (SD) of all spots was larger than 0.25. Thresholds for copy number gain and loss were defined as $\log_2$ ratios of +2 SD and −2 SD, respectively. The reproducibility of the data was confirmed in two independent experiments for each tumor sample. For two representative cases, the consistency of the CGH results was confirmed by dye-swap experiments, in which tumor and reference DNA were inversely labeled with Cy3 and Cy5, respectively.

FISH Analysis

Interphase FISH experiments were performed as previously described (Wang et al., 2003).

RESULTS

Quality Test of BAC Array

Prior to the analysis of CML samples, control experiments were performed to evaluate the quality of the Human 1M array, in which DNA from normal individuals was used as a test sample. In the male-versus-male control hybridizations, $\log_2$ ratios for all spots were within the thresholds of −0.2 and 0.2 (Fig. 1a), whereas in the female-versus-male hybridizations, copy number gain of the whole chromosome X and copy number loss of the whole chromosome Y were detected successfully (Fig. 1b). In the latter experiments, the mean $\log_2$ ratios of the clones on the X and Y chromosomes were 0.435 ± 0.124 and −0.807 ± 0.167, respectively, compared to the mean $\log_2$ ratio of −0.008 ± 0.083 for all clones from autosomal chromosomes.

Higher Frequency of DNA Copy Number Changes in CML in BC and AP

A total of 55 CML samples in different stages were analyzed for copy number alterations by array CGH using Human 1M arrays. Table 2 lists the copy number alterations detected in individual

TABLE 2. Gains and Losses Detected by Array CGH

Case No.	Regions and clones that showed copy number gains	Regions and clones that showed copy number losses
AP1	3q26.2–q29 (RP11-91A17~RP11-233N20), 7p15.2–p14.3 (RP11-81F15~RP11-89N17)	22q13.2–q13.31 (RP11-81N15~RP11-66M5)
AP2	9p21.2 (RP11-81B19)-qter, Chromosome13, Chromosome19, Chromosome21, Chromosome22, ***22q11.1–q11.22 and 9q34.13–qter*** 22q13.1–q13.32 (RP11-4H24-RP11-133P21)	**8p23.1 (RP11-287P18)**
AP3	**5p15.1 (RP11-88L18, RP11-90B23), 19p13.2 (RP11-79F15)**	none
AP4	**8q21.2 (RP11-90G23)**	none
BC1	none	none
BC2	none	none
BC3	**4p15.33 (RP11-143120), 5p15.1 (RP11-88L18)** 8p12 (RP11-274F14-RP11-100B16), 9q, **19p13.2 (RP11-79F15)**, ***22q11.1–q11.22 and 9q34.13–qter***	**1q25.1 (RP11-177M16)**, 5q23.1–q23.3 (RP11-47L19-RP11-89G4), 5q31.2–q32 (RP11-11514~RP11-88H2), 7q31.1–q31.33 (RP11-79G19~RP11-90C13), 8pter–p12 (RP11-91P13), 9p
BC4	**8p23.1 (RP11-287P18), 22q11.21 (RP11-278E23)**	none
BC5	**8p23.1 (RP11-287P18), 17p13.3 (RP11-582C6), 19p13.2 (RP11-79F15)**	**17q21.31 (RP11-52N13)**
BC6	none	**5p15.1 (RP11-88L18)**
BC7	Chromosome8	none
BC8	none	none
BC9	none	**21q22.12 (RP11-17O20)**
BC10	**8p23.1 (RP11-287P18), 17p13.3 (RP11-582C6)**	none
BC11	none	none
BC12	**8p23.1 (RP11-287P18), 17p13.3 (RP11-582C6)**	**5p15.1 (RP11-88L18)**
BC13	none	Chromosomes 4 and 13
BC14	Chromosome8, **8q21.2 (RP11-90G23)**	none
BC15	**8p23.1 (RP11-287P18)**	none
BC16	Chromosome8*, **8p23.1 (RP11-287P18)**, Chromosome12*, **17p13.3 (RP11-582C6)**, ***22q11.1–q11.2 and 9q34.13–qter***	2q36.2–q37.3 (RP11-68H19~RP11-90E11*), 18pter–q11.2 (RP11-79F3)*
BC17	none	**1q25.3 (RP11-196B7), 17q21.31 (RP11-52N13)**
BC18	none	**1q25.3 (RP11-173E24), 1q25.3–q31.1 (RP11-162L13)**
BC19	none	**5p15.1 (RP11-88L18)**, 7p21.3–p11.2 (RP11-79O21~RP11-90N11)
BC20	none	**9q22.32 (RP11-223A21)**
BC21	**5p15.1 (RP11-88L18)**, Chromosome19*, ***22q11.1–q11.2 and 9q34.13–qter***	none
BC22	6p22.3 (RP11-43B4~RP11-288M24), 8p21.3 (RP11-89O4~RP11-274M9), 8p11.21 (RP11-282J24)-qter	8pter–p11.2 (RP11-284J3)
BC23	**5p15.1 (RP11-88L18)**	none
BC24	Chromosome8*, **17p13.3 (RP11-582C6), 17q22 (RP11-143M4)** ***22q11.1–q11.2 and 9q34.13–qter***	**5p15.1 (RP11-88L18), 7q11.21 (RP11-90C3)**
BC25	**5p15.1 (RP11-88L18), 19p13.2 (RP11-79F15)**	none
BC26	8q24.13–q24.21 (RP11-229L23-RP11-237F24), 19p13.2–p12 (RP11-84C17~RP11-91L5), ***22q11.1–q11.2 and 9q34.13–qter***	none
CP1	**8p23.1 (RP11-287P18), 17p13.3 (RP11-582C6)**	**1q25.1 (RP11-177M16), 1q25.3 (RP11-173E24), 5p15.1 (RP11-88L18)**
CP2	**17q21.31 (RP11-52N13)**	**1q25.1 (RP11-177M16)**
CP3	**17p13.3 (RP11-582C6), 17q12(CTD-2019C10)**	**5p15.1 (RP11-88L18), 17q25.2 (RP11-145C11)**

(Continued)

TABLE 2. Gains and Losses Detected by Array CGH (Continued)

Case No.	Regions and clones that showed copy number gains	Regions and clones that showed copy number losses
CP4	**5p15.1 (RP11-88L18), 19p13.2 (RP11-79F15)**	**1q25.1 (RP11-177M16), 17q21.31 (RP11-52N13)**
CP5	none	none
CP6	none	**5p15.1 (RP11-88L18)**
CP7	**19p13.2 (RP11-79F15)**	none
CP8	none	Chromosome3
CP9	none	none
CP10	none	none
CP11	none	none
CP12	**6q25.3–q26 (RP11-43B19)**	none
CP13	**8p23.1 (RP11-287P18), 17p13.3 (RP11-582C6)**	none
CP14	**19p13.2 (RP11-79F15)**	none
CP15	8p23.2 (RP11-113B7~RP11-89I12), **8p23.1 (RP11-287P18), *22q11.1–q11.2 and 9q34.13–qter***	none
CP16	**19p13.2 (RP11-79F15)**	**8q21.2 (RP11-90G23)**
CP17	none	none
CP18	**17p13.3 (RP11-582C6)**, 17p11.2–qter	**17q12(CTD-2019C10)** 17pter–p12
CP19	none	none
CP20	**19p13.2 (RP11-79F15)**	**5p15.1 (RP11-88L18)**
CP21	**8p23.1 (RP11-287P18), 15q22.31 (RP11-50N10), 22q13.32 (RP11-133P21)**	**1q25.1 (RP11-177M16)**
CP22	none	none
CP23	none	none
CP24	none	**5p15.1 (RP11-88L18, RP11-90B23), 8q21.3 (RP11-91K2), 9q32 (RP11-95J4)**
CP25	none	none

22q11.1–11.2 and ***9q34.13–qter*** corresponds to Philadelphia chromosome.
Gain of 17p11.2–qter together with loss of 17pter–p12 represents isochromosome 17q (i(17q)).
Copy number changes involving a single BAC are indicated in bold. Underlined are the regions (or BAC loci) whose copy number changes were confirmed by FISH.

cases, and Table 3 summarizes the number of cases showing each copy number alteration in different stages of CML. Array CGH successfully detected cryptic gains and losses that had been missed by conventional karyotyping analysis as well as large chromosomal changes that had been observed in prior conventional karyotyping analysis (Tables 2 and 3).

When analysis was confined to copy number alterations that involved at least two consecutive BAC clones, only 4 copy number alterations were detected in 25 patients in CP, whereas 38 copy number alterations were identified in 30 patients in AP/BC (Table 2). The frequency of DNA copy number alterations was significantly higher in AP/BC than in CP ($P < 0.005$).

Large and Small Cryptic Changes Detected by High-Resolution Array CGH

In the current analysis, the most frequent alteration was gain of extra Ph chromosomes (6 cases in AP/BC, 1 case in CP), which was inferred from gains of a distal part of 9q and a proximal part of 22q. Alterations of whole chromosomes, including gains of chromosomes 8 (4 cases in BC), 19 (2 cases in AP/BC), 13, 21, and 22 (1 case each in AP), and losses of chromosomes 3 (1 case in CP), 4, and 13 (1 case each in BC) were also observed (Tables 2 and 3). One CP patient (case CP18) displayed both gain of 17p11.2–qter and loss of 17pter–p12 material, suggesting the presence of an isochromosome 17q—i(17q)—which has repeatedly been reported in association with CML BC (Prigogina et al., 1978; Alimena et al., 1987; Fioretos et al., 1999; Melo et al., 2003), although the conventional karyotyping analysis had missed this abnormality.

Our array CGH analysis also uncovered cryptic changes that had not been reported in CML and therefore were novel regions implicated in the pathogenesis and progression of CML. Case BC3 was found to have a balanced t(9;22) translocation as the sole chromosomal abnormality in karyotyp-

TABLE 3. Summary of Copy Number Alterations Detected by Array CGH

	Stage	
	CP ($n = 25$)	AP + BC ($n = 30$)
Gains		
Unbalanced translocations or gains that were also detected by G-banding analysis		
Ph (22q11.1–q11.2 and 9q34.13–qter)	0	3
Chromosome 8	0	2
Chromosome 13	0	1
Chromosome 19	0	2
Chromosome 21	0	1
Chromosome 22	0	1
Gains in cases in which G-banding analysis was not done		
Chromosome 8	0	1
3q26.2–q29	0	1
7p15.2–p14.3	0	1
8p11.21–q24.3	0	1
Cryptic gains that were not detected by G-banding analysis (involving at least two consecutive BAC clones spotted on the array)		
Ph (22q11.1–q11.2 and 9q34.13–qter)	1	3
i(17q) (gain of 17p11.2–qter and loss of 17pter–p12)	1	0
Chromosome 8	0	1
6p22.3	0	1
8p12	0	1
8p21.3	0	1
8p23.2	1	0
8q24.13–q24.21	0	1
9p21.2–qter	0	1
9q	0	1
19p13.2–p12	0	1
22q13.1–q13.32	0	z1
Total number	3	26
Losses		
Losses in cases in which G-banding analysis was not done		
Chromosome 3	1	0
Chromosome 4	0	1
Chromosome 13	0	1
7p21.3–p11.2	0	1
22q13.1–q13.31	0	1
Cryptic losses that were not detected by G-banding analysis (involving at least two consecutive BAC clones spotted on the array)		
2q36.2–q37.3	0	1
5q23.1–q23.3	0	1
5q31.2–q32	0	1
7q31.1–q31.33	0	1
8pter–p12	0	1
8pter–p11.2	0	1
9p	0	1
18pter–q11.2	0	1
Total number	1	12

ing analysis (Tables 1 and 2). However, in array CGH, multiple copy number alterations, including gains in 8p12 and 9q, and an extra Ph chromosome, and losses in 5q23.1–q23.3, 5q31.2–q32, 7q31.1–q31.33, 8pter–p12, and 9p were reproducibly detected in duplicate experiments (Table 2, Fig. 2a). Case BC16 had a karyotype showing 48,XY, t(3;21;18)(q21;q22;p11),+8, t(9;22)(q34;q11), +12 (Table 1), whereas array CGH also detected an extra Ph chromosome as well as losses in 2q36.2–q37.3 and 18pter–q11.2 (Table 2, Fig. 2b). Also, in case BC22, CGH analysis disclosed cryptic copy number gains in three consecutive BACs within a small 6p22.3 region spanning 505 kb (Table 2, Fig. 2c).

These array CGH results were confirmed by FISH analysis using affected BAC clones as probes when Carnoy samples were available (Table 2, Fig. 2b and c). For example, the sample from patient BC16 showed, consistent with trisomies 8 and 12, three signals from clones RP11-150N13, on chromosome 8 (with an average $\log_2$ ratio of 0.449), and RP11-91I15, on chromosome 12 (with an average $\log_2$ ratio of 0.474), whereas clones RP11-116M19, on chromosome 2 (with an average $\log_2$ ratio of −0.538), and RP11-105C15, on chromosome 18 (with an average $\log_2$ ratio of −0.701), produced only one signal, confirming the presence of an allelic deletion in these regions (Fig. 2b). In patient BC22, clones RP11-228M24, at 6p22.3 (with an average $\log_2$ ratio of 1.158), showed multiple signals, in agreement with the copy number gain found in array CGH (Fig. 2c).

Copy number changes that involved only a single BAC locus (Table 4) were verified by FISH analysis for selected cases (Table 2 and Fig. 2d). In total, 75 single BAC copy number changes (SBCs) were identified in 24 BAC loci among 55 CML patients. Because 35 of the 75 SBCs, found in three BAC loci, were also identified in normal individuals (3 SBCs, at RP11-88L18, RP11-287P18, and RP11-586C6, in 10 healthy Japanese individuals; data not shown) and 37 SBCs in six BAC loci appeared as both copy number gains and losses depending on samples, suggesting that many of these are likely to represent polymorphisms known as large-scale copy number variations (LCVs; Iafrate et al., 2004; Sebat et al., 2004; Table 4). Indeed, 11 of the 24 BAC loci showing SBCs conformed to regions previously reported as LCVs (Table 4) (Iafrate et al., 2004; Sebat et al., 2004).

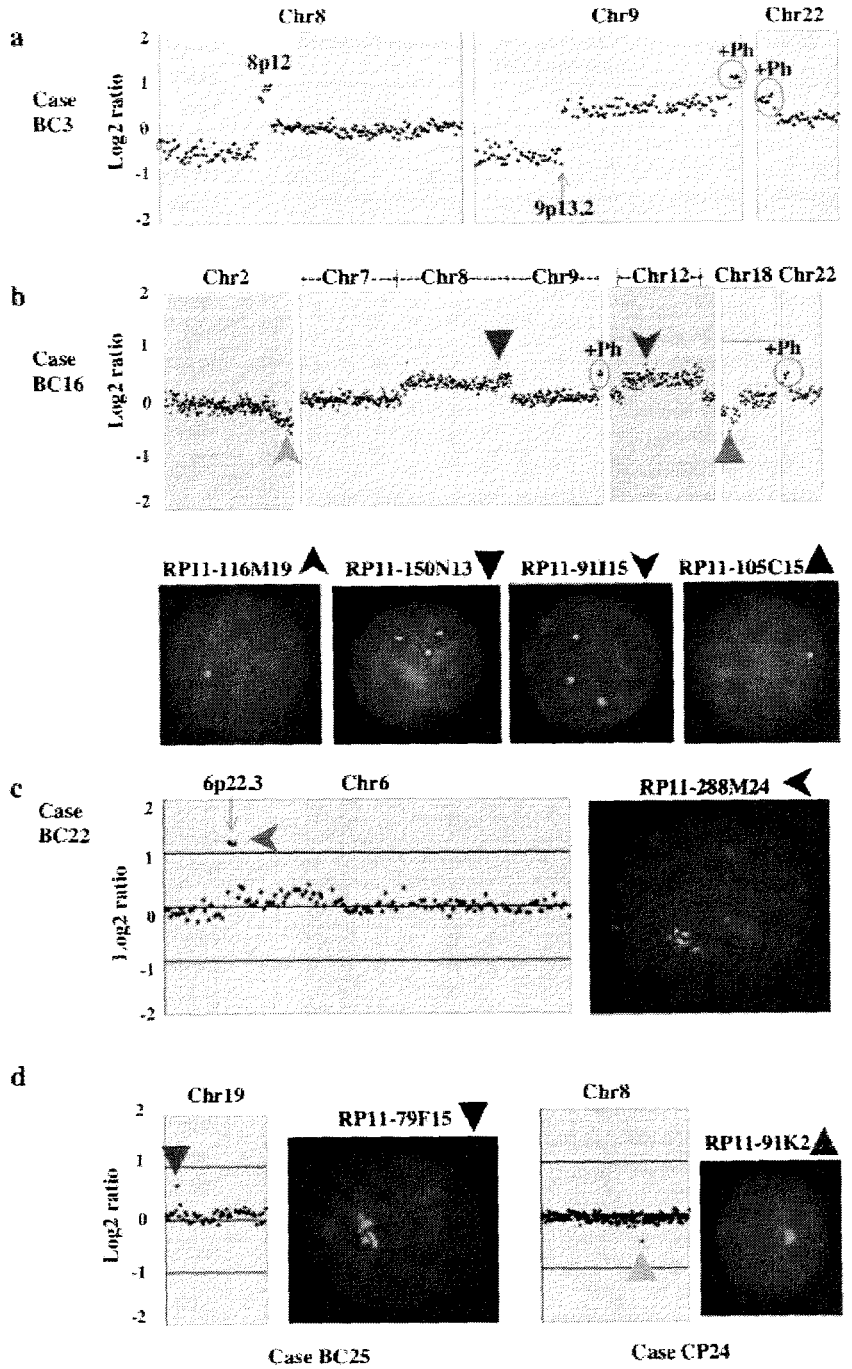

Figure 2. Gains and losses detected by array CGH and confirmed by FISH analysis. (a) Array CGH profile of case BC3, showing an extra Ph chromosome, gains in 8p12 and 9q and losses in 8pter–8p12 and 9p, not detected by karyotyping analysis; (b) Array CGH profile of case BC16, in which an extra Ph chromosome, gain in chromosome 8 with a higher-level of gain of the clone RP11-287P18, gain in chromosome 12, and losses in 2q36.2–2q37.3 and 18pter–18q11.2 were identified. Interphase FISH analysis of this case used the indicated biotin-labeled BAC clones as probes. Consistent with trisomies 8 and 12, clones RP11-150N13, on chromosome 8 (average $\log_2$ ratio of 0.449), and RP11-91I15, on chromosome 12 (average $\log_2$ ratio of 0.474), showed 3 signals, whereas clones RP11-116M19, on chromosome 2 (average $\log_2$ ratio of −0.538), and RP11-105C15, on chromosome 18 (average $\log_2$ ratio of −0.701), produced only one signal, confirming an allelic deletion in these regions. (c) Array CGH profile of case BC22, for which clone RP11-288M24, at chromosome 6p22.3 (average $\log_2$ ratio of 1.158), showed multiple signals, confirming copy number gains in this region. (d) Array CGH profiles of cases BC25 and CP24, in which single BAC copy number changes were observed. Copy number gain (RP11-79F15) and loss (RP11-91K2) were verified by FISH analysis.

Candidate Genes Implicated in Pathogenesis or Disease Progression of CML

The regions showing gain or loss in DNA copy number or breakpoint regions of unbalanced chromosomal translocations could harbor one or more genes implicated in the pathogenesis of CML or disease progression to BC. Supplementary Table 2 lists the representative genes within these regions identified in this study, not including the single BAC regions showing both gains and losses. Among previously reported cellular oncogenes or leukemia-related genes were *EVI1* (3q26), *FGFR1* (8p12), and *MYC* (8q24), which were included in the regions showing copy number gains in 3q26.2–q29, 8p12, and 8q24.13–q24.21, respectively (Supplementary Table 2). The 505-kb region showing

TABLE 4. Copy Number Alterations Involving a Single BAC Locus

	Stage	
	CP ($n = 25$)	AP + BC ($n = 30$)
Gains		
4p15.33 (RP11-143I20)[a]	0	1
5p15.1 (RP11-88L18)[a]	1	5
5p15.1 (RP11-90B23)	0	1
6q25.3–q26 (RP11-43B19)[a]	1	0
8p23.1 (RP11-287P18)[a]	4	6
8q21.2 (RP11-90G23)[a]	0	2
15q22.31 (RP11-50N10)	1	0
17p13.3 (RP11-582C6)[a]	4	5
17q12 (CTD-2019C10)	1	0
17q21.31 (RP11-52N13)	1	0
17q22 (RP11-143M4)	0	1
19p13.2 (RP11-79F15)[a]	4	4
22q11.21 (RP11-278E23)[a]	0	1
22q13.32 (RP11-133P21)	1	0
Losses		
1q25.1 (RP11-177M16)	4	1
1q25.3 (RP11-196B7)	0	1
1q25.3 (RP11-173E24)	1	1
1q25.3–q31.1 (RP11-162L13)	0	1
5p15.1 (RP11-88L18)[a]	5	4
5p15.1 (RP11-90B23)	1	0
7q11.21 (RP11-90C3)[a]	0	1
8p23.1 (RP11-287P18)[a]	0	1
8q21.2 (RP11-90G23)[a]	1	0
8q21.3 (RP11-91K2)[a]	1	0
9q32 (RP11-95J4)[a]	1	0
9q22.32 (RP11-223A21)	0	1
17q12 (CTD-2019C10)	1	0
17q21.31 (RP11-52N13)	1	2
17q25.2 (RP11-145C11)	1	0
21q22.12 (RP11-17O20)	0	1

Shaded areas point to the loci that showed both gains and losses in different samples.
[a]Regions previously reported to show large-scale copy number variations (LCVs).

copy number gain at the chromosome band 6p22.3 contained *OACT1* (*O*-acetyltransferase domain containing 1) and *E2F3* (E2F transcription factor 3), both known genes (Supplementary Table 2). It is not clear whether this region overlapped with the breakpoint region of the recurrent translocations t(6;19)(p22;q13) and t(6;9;22)(p22;q34;q11) in CML (Huret et al., 1989; Meza Espinoza et al., 2004; Yehuda et al., 1999), because the precise molecular breakpoints at 6p22 in these cases have not been characterized. The 346-kb region at 8p23.2 that showed copy number gain includes *CSMD1* (CUB and sushi multiple domains protein 1 precursor), the only transcriptome (Supplementary Table 2). Other abnormalities newly identified in this study involved mostly large regions of 2q26.2–q37.3 (16.8 Mb), 5q23.1–q23.3 (10.6 Mb), 5q31.2–q32 (6.50 Mb), 7p15.2–p14.3 (6.14 Mb), 7p21.3–p11.2 (41.7 Mb), 7q31.1-q31.33 (17.9 Mb), 8p21.3 (2.18 Mb), and 19p13.2–p12 (12.1 Mb), which made it difficult to pinpoint the candidate target genes.

DISCUSSION

In this article, we have shown genomewide detection of DNA copy number changes in a total of 55 CML patients at different stages using high-resolution array CGH. Using this technique, we delineated not only previously reported abnormalities, but also novel alterations involving narrow regions that may harbor only one or several candidate genes involved in the pathogenesis or disease progression of CML.

A number of cryptic copy number alterations that had been missed by karyotyping analysis were detected in array CGH analysis. Seven patients were found to have extra Ph chromosomes, which was the most frequent alteration in our series, although this alteration had not been detected by prior G-banding analysis in four of the seven patients (57%). In addition, more than 10 novel, cryptic copy number alterations were uncovered at a significantly higher frequency in patients in BC and AP, suggesting that these regions may contain genes relevant to the pathogenesis of CML, especially in progressive stages. Considering the wide variety of copy number alterations detected in AP/BC cases and that the majority of these abnormalities were observed in a single patient in our series, there might be a large heterogeneity in the molecular pathogenesis of CML AP/BC cases, and it may be possible that analysis of a larger number of patients could disclose novel recurrent molecular defects in CML. Alternatively, the genes included in the affected regions may also be deregulated by other mechanisms such as point mutations or epigenetic effects, which could not be detected by copy number analysis.

Many of the cryptic gains or losses affecting a single BAC locus are thought to represent copy number polymorphisms or LCVs rather than tumor-specific changes, and given their high frequency, it would be difficult to discriminate tumor-specific changes from LCVs. In our analysis, SBCs (or LCVs) seemed to be more frequently found in CML than in normal individuals using the same reference set (55 of 75 in CML vs. 3 of 10 in normal individuals, $P = 0.021$). Although

recent reports suggested a possible association of some LCVs with the regions implicated in cancer development (Iafrate et al., 2004; Sebat et al., 2004), the precise role of the LCVs detected in the current analysis in the pathogenesis of CML is still unclear and should be addressed in future studies that would include a larger number of normal subjects.

Although array CGH analysis successfully unveiled cryptic genomic aberrations in CML, we should note that it also has limitations in that the tumor content of the samples clearly affected the sensitivity of detecting copy number changes in tumor components. According to our admixture experiments, in which mixed tumor and normal DNA were tested for detection of a trisomy, the threshold of tumor content for detection of trisomies in our array CGH was estimated to be more than 20%–40% tumor components (data not shown). Thus, the trisomy 8 in AP3 and the monosomy 21 in AP4 as revealed by G-banding analysis were not expected to be detected in array CGH analysis because abnormal metaphases were found in only 2 of 20 with AP3 and 5 of 20 with AP4 (Tables 1 and 2). On the other hand, array CGH failed to detect the loss of chromosome 21 found in 17 of 20 metaphases in G-banding analysis in BC26, which was most likely a result of karyotypic overrepresentation of one or more rapidly proliferating tumor subclones in G-banding analysis. Finally, the FISH Mapped Clones V1.3 collection distributed from BACPAC Resources Center, which we used for array construction, does not cover some regions of particular interest in CML pathogenesis. For example, deletions of the 5′ region of the *ABL/BCR* junction on the der(9) chromosome, which is known to affect 10%–15% of the CML patients (Storlazzi et al., 2002), were missed in this study because our Human 1M arrays did not contain BAC clones including the *ABL* gene or the upstream *ASS* gene.

In conclusion, our array CGH analysis disclosed not only common chromosomal abnormalities, but also small, cryptic copy number alterations in CML genomes that were not detected by conventional analysis. It enabled a better description of genetic alterations in CML, which potentially could be applicable to molecular diagnostics and prediction of disease prognosis of this neoplastic disorder. The submicroscopic copy number alterations detected in this study might contribute to the identification of novel molecular targets implicated in the pathogenesis or disease progression of CML. Further studies with whole-genome tiling arrays having much higher resolutions will help to detect precisely the genes involved in the disease progression of CML.

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