Routine Cytogenetic Analysis of Chromosome Abnormalities in Acute Lymphoblastic Leukemia

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Abstract
Acute lymphoblastic leukemia (ALL) is the most common cancer in children. Acquired chromosomal and genetic abnormalities have been used to define distinct biological and clinical subtypes of ALL. These aberrations have been shown to be associated with patient outcome and are used to direct therapy. Conventional cytogenetics analysis (CCA) is currently the gold standard to detect chromosome abnormalities in hematological malignancies. In this review we briefly describe the CCA methodology, advantages and limitations of CCA, the main chromosomal abnormalities and their prognostic significance in ALL.

Keywords: Acute lymphoblastic leukemia, chromosome abnormalities, prognosis.

1. Introduction
Acute lymphoblastic leukemia (ALL) is a neoplastic disease characterised by clonal expansion of white cell precursors in the bone marrow, lymph nodes, thymus or spleen. ALL shows a bimodal age distribution, with a high incidence at ages 1-4 years, a decline at ages 20 to 59 years, followed by a modest rise in incidence above age 60 years [1]. About 75% of ALL occurs in children under 6 years of age. B-lineage ALL is more frequent than T-lineage ALL, accounting for 85% of childhood ALL and 75% of adult ALL [2]. The survival rate of pediatric ALL has improved to about 90% with risk stratification, but however the prognosis of infants and adults remains poor [3]. Most modern treatment protocols stratify patients according to prognostic factors such as genetics, age, white cell count, immunophenotype, and response to therapy. Acquired genetic abnormalities define distinct biological and clinical subtypes of ALL, and are one of the most powerful predictors of outcome in ALL. About 75% of childhood ALL harbor recurrent genetic chromosomal abnormalities, including aneuploidy or structural chromosomal arrangements [4].

The World Health Organization (WHO) classification of B-lineage lymphoblastic leukemia/lymphoma identifies 7 subtypes with recurrent genetic abnormalities: t(9;22)(q34;q11.2), BCR-ABL1; t(v;11q23), MLL rearranged; t(12;21)(p13;q22), ETV6-RUNX1; hyperdiploidy; hypodiploidy; t(5;14)(q31;q32), IL3-IGH; and t(1;19)(q23;p13.3), TCF3-PBX1 [5]. Most of these specific abnormalities may be detected by routine cytogenetic analysis, except for t(12;21)(p13;q22), ETV6-RUNX1 which is a submicroscopic rearrangement that is detectable by FISH (fluorescence in situ hybridization) or RT-PCR (reverse transcriptase polymerase chain reaction).

There are many genetic techniques that can be utilised to detect chromosomal and genomic aberrations in patients with ALL. The spectrum of genetic abnormalities in ALL is very wide and diverse, and no single technique is able to detect all types of aberration. Despite the invention of novel technologies, conventional cytogenetic analysis (CCA) is currently the foundation genetic test in ALL. In this article we briefly describe the CCA methodology, some limitations of cytogenetic analysis, the recurrent chromosomal abnormalities and their prognostic significance in ALL.
2. Conventional Cytogenetic Analysis

CCA is commonly used as a routine diagnostic test to detect chromosomal abnormalities in hematological malignancies. It can identify all chromosomal aberrations present simultaneously (that are visible under the microscope) in a leukemic cell.

a) Sample requirements and cultures

The preferred sample for CCA is bone marrow aspirate collected in a heparinised container and transported as soon as possible (in ice) to the Cytogenetics Laboratory. If the bone marrow aspirate is not available, then trephine biopsies or peripheral blood (if blasts are present) may be cultured. Cell counting should be performed for optimisation of cell culture. An overnight unstimulated culture (<24 hrs) should be set up as some ALL cells may have an increased tendency for apoptosis. If there are sufficient cells, an additional 48-hr culture may be initiated. The addition of growth factor supplements such as stem cell factor, interleukins, and Flt3-ligand may increase chromosome quality in B-lineage ALL [6]. For T-lineage ALL, additional cultures stimulated with phytohemagglutinin may be set up.

b) G-banded karyotyping

Karyotyping is according to the International System of Human Cytogenetic Nomenclature (ISCN2013) [7] at the time of analysis. A minimum of 20 metaphases must be analysed if there is no clonal abnormality. Chromosomal aberrations when detected must be clonal (when present in a minimum of two cells with the same extra chromosomes or structural aberrations, or at least three cells with the same chromosome loss). Near-haploidy (<30 chromosomes) and low hypodiploidy (30–39 chromosomes) may undergo clonal evolution and double-up as hyperdiploid and near-triploid metaphases respectively [8]. Near-haploidy and low hypodiploidy confer a poor prognosis and are assigned to high risk therapy. In the event of finding an atypical hyperdiploid or near-triploid karyotype with four copies of chromosomes other than 21 or the sex chromosome, one must investigate the possibility of an underlying near-haploid or low hypodiploid population. Investigations may include interphase FISH, and consideration could be given to short tandem repeat (STR) analysis and zygosity testing [9].

c) Limitations of Cytogenetic Analysis

CCA is a biological test which depends on dividing cells for analysis. Sometimes, the processed samples yield no or only a few analyzable metaphase cells, or the karyotypes obtained were of poor quality to allow interpretation. Another limitation is the inability to detect small or subtle abnormalities such as cryptic translocations and insertions. The t(12;21)(p13;q22) translocation is cryptic where the breakpoints involves similarly banded regions and thus cannot be identified by G-banding. Although the BCR-ABL1 gene is usually generated by the typical t(9;22)(q22;q11.2) translocation, submicroscopic insertion of the BCR-ABL1 fusion gene resulting in normal chromosomes 9 and 22 have also been reported [10]. These two major limitations of cytogenetics may be overcome by the incorporation of additional targeted tests such as FISH and RT-PCR.

3. Chromosomal Abnormalities in B-lineage ALL (B-ALL)

Chromosome abnormalities in B-ALL can be divided into 3 main groups: (i) chromosomal translocations which result in the formation of novel chimeric fusion genes leading to expression of leukemogenic proteins or over-expression of oncogenes, (ii) ploidy subgroups characterised by the gain or loss of multiple non-random chromosomes, and (iii) miscellaneous subgroups. Translocations account for about 40-50% of ALL. There is also a strong correlation between age and frequency of types of chromosomal abnormalities. Ploidy subgroups are defined according to the number of chromosomes present in the major leukemia clone, and are more prevalent in children (40%) than adults (20%) [11].

a) Primary Chromosomal Abnormalities

(i) Chromosomal Translocations / gene fusions

The translocation t(12;21)(p13;q22) results in the fusion gene ETV6-RUNX1 and is most prevalent in pediatric ALL (about 25%), but is rare in adults. The translocation is detectable using FISH or RT-PCR. Children with ETV6-RUNX1 fusion have excellent overall survival with very low relapse rates. Patients with t(12;21) also harbour additional chromosomal abnormalities (ADA) such as deletions of 12p with the loss of ETV6 gene (55-70% of patients), +21 (15-20%), or an extra derivative chromosome 21, der(21)t(12;21) [10-15%]. Studies have shown that these ADA do not have any impact on survival [12].

The translocation t(1;19) is present in about 3-5% of ALL. About 90-95% of the translocation t(1;19)(q23;p13) results in the fusion of TCF3 (formerly known as E2A) gene with PBX1 gene. About 50% of the translocation t(1;19) is balanced giving rise to TCF3-PBX1 fusion, while the other 50% is unbalanced with only the derivative chromosome, der(19)t(1;19) and with no TCF3-PBX1 fusion [13]. Patients with TCF3-PBX1 fusion usually have a pre-B immunophenotype expressing
cytoplasmic μ. With the use of modern intensive therapy, pediatric ALL patients with t(1;19) have an intermediate/good response [14]. In adults with t(1;19), the prognosis remains controversial, with some studies reporting poor outcomes while others found to association with outcome.

Translocations involving the MLL (mixed lineage leukemia) gene on 11q23 with other partner genes have been reported in both ALL and acute myeloid leukemia (AML). The most common MLL translocation in ALL is the t(4;11)(q21;q23)/MLL-AFF1 (formerly known as AF4), with a low incidence in children (2-3%), and an increase in the incidence with age among the adults. Patients with t(4;11) have a poor prognosis, but with the use of modern aggressive therapy especially in children their outcome has improved [15]. The prognosis of patients with other MLL translocations is still uncertain. However, infants and young children (< 3 years) with MLL translocations have a very poor prognosis.

The translocation t(9;22)(q34;q11.2) results in the generation of the Philadelphia (Ph) chromosome. The BCR-ABL1 fusion gene formed then translates a protein with tyrosine kinase activity. The t(9;22) had been reported in chronic myeloid leukemia (CML), AML and ALL. Ph-positive ALL is characterised by presence of intragenic deletion of the IKZF1 (Ikaros) gene, which is not found in Ph-positive CML and AML [16]. The incidence of Ph-positive ALL increases with age from 2% in children to 29% in adults (30-39 years), and to 40% in older adults (40+ years). Although the Ph chromosome in ALL is associated with a poor prognosis, treatment with tyrosine kinase inhibitors have improved the event free survival rates of ALL patients compared to patients treated with traditional chemotherapy and stem cell transplantation [17, 18]. However, Ph-positive ALL with IKZF1 deletions has an unfavourable outcome even with imatinib therapy compared to those with IKZF1 wild-type [19, 20]. Gene expression profiling (GEP) has also identified ‘BCR-ABL1-like’ B-ALL which is found in 15% of childhood B-ALL. BCR-ABL1-like B-ALL shows a similar GEP to Ph+ B-ALL, and is also associated with a poor prognosis, but without BCR-ABL1 rearrangement [21].

Immunoglobulin heavy chain (IGH) translocations involve deregulation of an oncogene via its juxtaposition to the IGH enhancer at 14q32. These translocations are recurrent but are rare in B-ALL, occurring in less than 5% of cases [22]. Five members of the CEBP family gene have been shown to undergo translocation with the IGH locus [23]. IGH translocations are prevalent in teenagers and young adults with ALL and are associated with a poor outcome [24]. The t(5;14)(q31;q32)/IGH-IL3 in B-ALL is associated with hyper eosinophilia and a poor prognosis.

The three genetic mechanisms which cause deregulation of CRLF2 (cytokine receptor-like factor 2 gene) are: a cryptic chromosomal translocation, t(X;14)(p22;q32) or t(Y;14)(p11;q32); a cryptic interstitial deletion, del(X)(p22.33)(p22.33) or del(Y)(p11.32p11.32); and an activating mutation. Studies on the prognosis of CRLF2 deregulation in childhood ALL show conflicting results whereas in adult ALL the outcome is inferior.

(ii) Ploidy Subtypes

Hy piodiploidy (less than 46 chromosomes) is seen in about 5-8% of B-ALL, with a majority of them having 45 chromosomes. The other types of hypodiploidy are much rarer, and they include near-haploidy (24-29 chromosomes), low-hypodiploidy (30-39 chromosomes) and high-hypodiploidy (40-44 chromosomes) [25]. About 1% of children (< 15 years) with ALL have a near haploid karyotype. Nullsomy, loss of both copies of a particular chromosome and structural abnormalities are rare. The chromosome loss is non random and the chromosomes frequently retained are chromosomes 10, 14, 18, 21 and the sex chromosomes (X/Y). Clonal evolution is common where the subclone is a double-up version of the primary clone. It is important to identify correctly near-haploidy especially when the double-up subclone might be mis-classified as hyperdiploid. Near-haploidy has a very poor outcome and requires high risk therapy [26].

Low hypodiploidy karyotypes (30-39 chromosomes) will usually be monosomic for chromosomes 3, 7, 15, 16, 17 and disomic for chromosomes 1, 6, 11 and 18. Subclones with near-triploid karyotypes (60-78 chromosomes) are common due to the phenomenon of doubling-up in low hypodiploid clones. In karyotypes with 60-65 chromosomes, correct identification of low hypodiploidy/ near-triploidy (LHNT) and high hyperdiploidy (HH) is necessary as LHNT has a poor prognosis. The pattern of chromosome gain can be used to identify HH and LHNT. HH are trisomic for chromosomes X, 4, 6, 10, 17 & 18, and tetrasomic for chromosomes 14 and 21. Double-up low hypodiploidy karyotypes are usually disomic for chromosomes 3, 7, 15, 16, 17 and tetrasomic for chromosomes 1, 6, 11 and 18 [27]. LHNT is rare among children but is present in 3-5% of adolescence adults.

HH is characterised by simultaneous gain of between 5 to 19 chromosomes, thus resulting in the leukemic cells having a total of 51 to 65
Chromosome abnormalities in ALL

The chromosome gain is non-random, mainly involving chromosomes X, 4, 6, 10, 14, 17, 18, and 21 [28]. HH is the most common genetic abnormality observed in ALL, and is associated with a favourable outcome. It is present in about 35% of children compared to 10% in adults. About 2.8% of childhood ALL with HH harbour either t(1;19), t(9;22), der(11q23) or t(12;21) [29]. Fig. 1 shows the karyotype of a child with B-ALL having HH detected by our Cytogenetics Laboratory.

Fig. 1 Karyotype of a female child with B-lineage acute lymphoblastic leukemia showing high hyperdipoidy

62,XX,+2,+4,+5,+6,+8,+10,+11,+12,+14,+17,+18,+20,+21,+21. Gain of chromosomes 2, 4, 5, 6, 8, 10, 11, 12, 14, 17, 18, 20 and 21. There is also gain of two chromosomes 8 and three chromosomes 21. Arrows indicate the chromosomes gained.

(iii) Miscellaneous Subgroup

Intrachromosomal amplification of chromosome 21(iAMP21) is found in about 3-5% of pediatric patients with ALL, usually between 7 and 13 years. This abnormal chromosome 21 has multiple regions of inversion, deletion, duplication and amplification along its entire length. The regions amplified always include the RUNXI locus and can be detected by using a FISH probe that targets RUNXI locus (e.g. ETV6-RUNXI dual fusion probe). However, there is no evidence that RUNXI gene is involved [30]. Patients with iAMP21 have a high risk of relapse and require more intensive therapy [31]. There is a 2700-fold increased risk of developing B-ALL with iAMP21 in people born with constitutional Robertsonian translocation [32].

The complex karyotype in ALL is defined as the presence of 5 or more unrelated chromosomal abnormalities in the absence of a known translocation. About 5-10% of Ph-negative B-cell ALL have a complex karyotype, which is associated with a poor outcome.

b) Secondary chromosomal abnormalities

The chromosomal abnormalities described above are considered as primary chromosomal abnormalities which define distinct biological and clinical subgroups of the disease. The t(9;22), t(12;21), iAMP21, and MLL rearrangements are reported to be mutually exclusive [2]. A majority of ALL patients at diagnosis harbour more than one genetic abnormality in the form of non random numerical and structural chromosome aberrations that can be detected microscopically. However, the application of genomic-wide molecular technologies (such as array comparative genomic hybridization and single nucleotide polymorphism array) also reveal many genetic abnormalities that are not detectable at the cytogenetics level [33]. These secondary additional chromosomal or genomic abnormalities (ACGA) have been found in virtually all chromosomes and all regions of the genome.
has been shown that the majority of ACGA are deletions rather than amplifications or duplications [34]. The common ACGA are deletions of CDKN2A/B (30-40%), deletions/mutations of IKZF1 gene (20%), deletions/mutations/amplifications of PAX5 gene (20%), and deletions of ETV6 (10-15%) [11, 35].

Chromosome abnormalities of 9p are associated with aberrations of CDKN2A/B and PAX5. Chromosome abnormalities such as del(13q), monosomy 13, 17p abnormalities are associated with a poor outcome in pediatric ALL, but when exist as secondary abnormalities with a favourable outcome abnormality such as high hyperdiploidy or ETV6-RUNXI, the good outcome of the abnormality is not abrogated [14]. IGH translocation have been reported to coexist together with primary rearrangements (e.g. High hyperdiploidy, t(12;21), t(9;22); MLL rearrangements, iAMP21 ) either in the same or separate clones, and when present, IGH translocation usually arise as secondary events. The IGH partner genes include CRLF2, CEBPA, CEBPB, TRA/D®, IGF2BP1 and IGK® [36]. Table 1 shows the non-random chromosome/genetic abnormalities, genes involved, and prognosis in B-ALL.

Table 1: Non-random chromosomal/ genetic abnormalities, genes involved and prognosis in B-lineage acute lymphoblastic leukemia [11]

| Chromosome / Genetic Abnormalities | Genes | Prognosis |
|-----------------------------------|-------|-----------|
| t(12;21)(p13;q22)                 | ETV6-RUNXI | Excellent |
| t(1;19)(q23;p13)                 | TCF3-PBX1 | Children: intermediate/good Adults: intermediate/poor Infants: very poor |
| t(17;19)(q22;p13)                | TCF3-HLF | Extremely poor |
| MLL (11q23) translocations       | MLL gene | Poor |
| t(9;22)(q34;q11.2)               | BCR-ABL1 | Very poor (unless treated with tyrosine kinase inhibitors) |
| IGH (14q32) translocations       | IGH1 gene | Poor |
| CRLF2 alterations                | CRLF2 gene | Children: Intermediate/ poor Adolescents & young adults: poor |
| iAMP21                           |        | Very poor (unless treated on high risk protocol) |
| Complex karyotype (>4 chr abnormalities) |       | Very poor |
| Near haploidy (<30 chrs)         |       | Very poor |
| Low hypodiploidy/ near triploidy (30-39/ 60-78 chrs) |       | Very poor |
| High hyperdiploidy (51-65/67 chrs) |       | Excellent |

Note: The prognostic impact of any given chromosome/ genetic abnormality depends not only on the treatment protocol, but may be modified by other risk factors such as age and presence of other genetic abnormalities.

4. Chromosomal Abnormalities in T-lineage ALL (T-ALL)

T-ALL has clinical, biochemical, immunologic, chromosomal aberrations that are distinct from B-ALL, an unfavourable prognosis, thus requiring more intensive therapy [37]. CCA revealed that chromosomal aberrations are found in about 60-70% T-ALL compared to 80-90% in B-ALL. Most of the recurrent chromosomal abnormalities in T-ALL are different from those in B-ALL. HH which is common in B-ALL are uncommon in T-ALL. Tetraploidy is present in about 3% of T-ALL but is of no prognostic significance. The nonrandom breakpoints within the T-cell receptor (TCR) gene cluster in T-ALL are: TCRA and TCRA at 14q11.2, TCRC at 7q34, and TRG at 7p15. Other chromosome abnormalities associated with T-ALL include breakpoints with 8q24 (MYC), 1p32 (TAL1), 9q32 (TAL2), 19p13 (LYL1), 21q22 (OLIG2), 11p15 (LMO1), 11p13 (LMO2), 10q24 (TLX1), 1p34 (LCK), and 9q34.3 (NOTCH1) [38].

A high number of T-ALL has cryptic cytogenetic abnormalities that can be detected by FISH or other molecular methods. CCA revealed that about 5-8% of T-ALL with abnormal karyotype have 7q34 (TCRB) abnormalities. However, molecular cytogenetics studies showed a higher incidence of TCRB rearrangements (20%). Cryptic deletions of the TAL1 (at 1p32) and the tumor suppressor gene CDKN2A (at 9p21) are found in 60% and 80% of patients respectively. At present there is no genetic abnormality in T-ALL that has been used for risk assessment. Overall survival outcomes are unaffected by the type of chromosome aberrations in T-ALL [38, 39]. The prognostic significance of T-ALL probably depends on the type and intensity of therapy given.

5. Discussion & Future Direction

Currently, CCA is the gold standard method for the identification of recurrent chromosomal abnormalities [40]. However, CCA has a low resolution (about 5-7 Mb), and is unable to detect...
submicroscopic genetic alterations. In a diagnostic cytogenetics laboratory for hematological malignancies, supplementary tests such as FISH and RT-PCR studies are usually performed as well. Although the five-year survival rate of children with ALL has exceeded 85%, survival after relapse remains poor [41]. Cytogenetic and molecular cytogenetic studies revealed chromosomal abnormalities in only about 80% of ALL [42]. However, genome-wide studies utilizing microarray-based techniques and next-generation sequencing (NGS) have shown that most ALL harbour sequence and structural DNA alterations involving coding genes and noncoding elements such as noncoding RNAs and enhancer elements [43]. These genetic alterations affect key cellular pathways in lymphoid development, tumor suppression, cell cycle regulation, cytokine receptor, ras signaling and chromatin modifications. These DNA changes also evolve over time from diagnosis to relapse, with the acquisition of new deletions and mutations, and loss of specific genetic lesions at diagnosis [44]. The incorporation of genomic findings would improve diagnosis and risk stratification in ALL, up to the delivery of targeted therapy. Recently, Moorman et al., (2014) [45] developed a novel integrated cytogenetic and genomic classification to refine risk stratification in pediatric ALL. NGS would probably be used to comprehensively identify all clinically relevant genomic alterations including sequence alterations, DNA copy-number alterations, and structural rearrangements in ALL. In future, genome sequencing when becomes cost-effective, may replace many of the diagnostic cytogenetics and molecular tests.

Conflict of Interest: None

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References
[1] Dores GM, Devesa SS, Curtis RE, Linet MS, Morton LM. Acute leukemia incidence and patient survival among children and adults in the United States, 2001-2007. Blood 2012; 119:34-43.
[2] Swerdlow SH, Campo E, Lee HN, Jaffe ES, Pileri SA, Stein H, et al. (Eds). WHO classification of tumours of haematopoietic and lymphoid tissues. Lyon: IARC; 2008.
[3] Hunger SP, Lu X, Devidas M, Camitta BM, Gaynon PS, Winick NJ, et al. Improved survival for children and adolescents with acute lymphoblastic leukemia between 1990 and 2005: a report from the children's oncology group. J Clin Oncol 2012; 30:1663-9.
[4] Mullighan CG. The molecular genetic makeup of acute lymphoblastic leukemia. Hematol Am Soc Hematol Educ Program 2012; 2012:389–396.
[5] Vardiman JW, Thiele J, Arber DA, Brunning RD, Borowitz MJ, Porwit A, et al. The 2008 revision of the World Health Organization (WHO) classification of myeloid neoplasms and acute leukemia: rationale and important changes. Blood 2009; 114:937-51.
[6] Fisher AM, Blair A, Strike P, Ross FM. B lymphoid growth factors significantly increase chromosome quality in cytogenetic cultures of ALL. J Med Genet 2007; 44, pp.S33.
[7] Shaffer LG, McGowan-Jordan J, Schmid M (eds). ISCN 2013: An International System for Human Cytogenetic Nomenclature, S. Karger, Basel 2013.
[8] Stark B, Jeison M, Gobuzov R, Krug H, Glaser Gabay L, Luria D, et al. Near haploid childhood acute lymphoblastic leukemia masked by hyperdiploid line: detection by fluorescence in situ hybridization. Cancer Genet Cyto genet 2001; 128:108-13.
[9] Professional Guidelines for Clinical Cytogenetics: Acute Lymphoblastic Leukemia v1.00 (2011); www.cytogenetics.org.uk.
[10] Robinson HM, Martineau M, Harris RL, Barber KE, Jalali GR, Moorman AV, et al. Derivative chromosome 9 deletions are a significant feature of childhood Philadelphia chromosome positive acute lymphoblastic leukemia. Leukemia 2005; 19:564-71.
[11] Moorman AV. The clinical relevance of chromosomal and genomic abnormalities in B-cell precursor acute lymphoblastic leukemia. Blood Reviews 2012; 26:123-135.
[12] Ko DH, Jeon Y, Kang HJ, Park KD, Shin HY, Kim HK, et al. Native ETV6 deletions accompanied by ETV6-RUNXI rearrangements are associated with a favourable prognosis in childhood acute lymphoblastic leukemia: a candidate for prognostic marker. Br J Haematol 2011; 155:530-3.
[13] Barber KE, Harrison CJ, Broadfield ZJ, Stewart AR, Wright SL, Martineau M, Strefford JC, Moorman AV. Molecular cytogenetic characterization of TCF3 (E2A)/19p13.3 rearrangements in B-cell precursor acute lymphoblastic leukemia. Genes, Chromosomes and Cancer 2007; 46:478-86.
[14] Moorman AV, Ensor HM, Richards SM, Chilton L, Schwab C, Kinsey SE, et al. Prognostic effect of chromosomal abnormalities in childhood B-cell precursor acute lymphoblastic leukemia: results from the UK Medical Research Council ALL97/99 randomised trial. Lancet Oncol 2010; 11:429-38.

[15] Moorman AV, Harrison CJ, Buck GA, Richards SM, Secker-Walker LM, Martineau M, et al. Karyotype is an independent prognostic factor in adult acute lymphoblastic leukemia (ALL): analysis of cytogenetic data from patients treated on the Medical Research Council (MRC) UKALLXII/Eastern Cooperative Oncology Group (ECOG) 2993 trial. Blood 2007; 109:3189-97.

[16] Mullighan CG, Miller CB, Radtke I, Phillips LA, Dalton J, Ma J, et al. BCR-ABL1 lymphoblastic leukemia is characterized by the deletion of Ikaros. Nature 2008; 453:110-4.

[17] Schultz KR, Bowman WP, Aledo A, Slayton WB, Sather H, Devidas M, et al. Improved early event-free survival with imatinib in Philadelphia chromosome-positive acute lymphoblastic leukemia: a children’s oncology group study. J Clin Oncol 2009; 27:5175-81.

[18] Stock W. Current treatment options for adult patients with Philadelphia chromosome-positive acute lymphoblastic leukemia. Leuk Lymphoma 2010; 51:188-98.

[19] Martinelli G, Iacobucci I, Storlazzi CT, Vignetti M, Paoloni F, Cillonzi D, et al. IKZF1 (Ikaros) deletions in BCR-ABL1-positive acute lymphoblastic leukemia are associated with short disease-free survival and high rate of cumulative incidence of relapse: a GIMEMA AL WP report. J Clin Oncol 2009; 27:5202-7.

[20] van der Veer A, Zaliova M, Mottadelli F, De Lorenzo P, TeKronnie G, Harrison CJ, et al. IKZF1 status as a prognostic feature in BCR-ABL1-positive childhood ALL. Blood 2014; 123:1691-8.

[21] Den Boer ML, van Slegtenhorst M, De Menezes RX, Cheok MH, Buijs-Giaddines JG, Peters ST, et al. A subtype of childhood acute lymphoblastic leukemia with poor treatment outcome: a genome-wide classification study. Lancet Oncol 2009; 10:125–134.

[22] Dyer MJ, Akasaka T, Capasso M, Dusanj P, Lee YF, Karran EL, et al. Immunoglobulin heavy chain locus chromosomal translocations in B-cell precursor acute lymphoblastic leukemia: rare clinical curios or potent genetic drivers? Blood 2010; 115:1490–9.

[23] Chapiro E, Radford-Weiss I, Cung HA, Dastugue N, Nadal N, Taviaux S, et al. Chromosomal translocations involving the IGH@ locus in B-cell precursor acute lymphoblastic leukemia: 29 new cases and a review of the literature. Cancer Genet 2013; 206:162-73.

[24] Russell LJ, Enshaei A, Jones L, Erhorn A, Masic D, Bentley H, et al. IGH@ translocations are prevalent in teenagers and young adults with acute lymphoblastic leukemia and are associated with a poor outcome. J Clin Oncol 2014; 32:1453-62.

[25] Harrison CJ, Moorman AV, Broadfield ZJ, Cheung KL, Harris RL, Reza Jalali G, et al. Three distinct subgroups of hypodiploidy in acute lymphoblastic leukemia. Br J Haematol 2004; 125:552-9.

[26] Nachman JB, Heerema NA, Sather H, Camitta B, Forester E, Harrison CJ, et al. Outcome of treatment in children with hypodiploid acute lymphoblastic leukemia. Blood 2007; 110:1112-5.

[27] Charrin C, Thomas X, Ffrench M, Le QH, Andrieux J, Mozziconacci MJ, et al. A report from the LALA-94 and LALA-SA groups on hypodiploidy with 30 to 39 chromosomes and near-triploidy: 2 possible expressions of a sole entity conferring poor prognosis in adult acute lymphoblastic leukemia (ALL). Blood 2004; 104: 2444-51.

[28] Paulsson K, Forester E, Liljebjörn H, Heldrup J, Behrendtz M, Young BD, Johansson B. Genetic landscape of high hyperdiploid childhood acute lymphoblastic leukemia. Proc Natl Acad Sci USA 2010; 107: 21719-24.

[29] Paulsson K, Forester E, Andersen MK, Autio K, Barbany G, Borgström G, et al. High modal number and triple trisomies are highly correlated favorable factors in childhood B-cell precursor high hyperdiploid acute lymphoblastic leukemia treated according to the NOPHO ALL 1992/2000 protocols. Haematologica 2013; 98:1424-32.

[30] Rand V, Parker H, Russell LJ, Schwab C, Ensor H, Irving J, et al. Genomic characterization implicates iAMP21 as a likely primary genetic event in childhood B-cell precursor acute lymphoblastic leukemia. Blood 2011; 117:6848-55.

[31] Heerema NA, Carroll AJ, Devidas M, Loh ML, Borowitz MJ, Gastier-Foster JM, et al. Intrachromosomal amplification of chromosome 21 is associated with inferior outcomes in children with acute lymphoblastic leukemia.
treated in contemporary standard-risk children's oncology group studies: a report from the children's oncology group. *J Clin Oncol* 2013; 31:3397-402.

[32] Li Y, Schwab C, Ryan SL, Papaemmanuil E, Robinson HM, Jacobs P, et al. Constitutional and somatic rearrangement of chromosome 21 in acute lymphoblastic leukemia. *Nature* 2014; 508:98–102

[33] Mullighan CG, Downing JR. Global genomic characterization of acute lymphoblastic leukemia. *Semin Hematol* 2009; 46:3-15.

[34] Paulsson K, Cazier JB, Macdougall F, Stevens J, Stasevich I, Vrcelj N, et al. Microdeletions are a general feature of adult and adolescent acute lymphoblastic leukemia: Unexpected similarities with pediatric disease. *Proc Natl Acad Sci USA* 2008; 105:6708-13.

[35] Mullighan CG, Goorha S, Radtke I, Miller CB, Coustan-Smith E, Dalton JD, et al. Genomewide analysis of genetic alterations in acute lymphoblastic leukemia. *Nature* 2007; 446:758-64.

[36] Jeffries SJ, Jones L, Harrison CJ, Russell LJ. *IGH* translocations co-exist with other primary rearrangements in B-cell precursor acute lymphoblastic leukemia. *Haematologica* 2014; 99(8):1334-42.

[37] Uckun FM, Sensel MG, Sun L, Steinherz PG, Trigg ME, Heerema NA, et al. Biology and treatment of childhood T-lineage acute lymphoblastic leukemia. *Blood* 1998; 91:735-46.

[38] Park J, Kim M, Lee HK, Kim Y, Han K, Son J, et al. Chromosome abnormalities in T-cell acute lymphoblastic leukemia in Korea. *Int J Hematol* 2014; 99:279-87.

[39] Marks DI, Paietta EM, Moorman AV, Richards SM, Buck G, DeWald G, et al. T-cell acute lymphoblastic leukemia in adults: clinical features, immunophenotype, cytogenetics, and outcome from the large randomized prospective trial (UKALL XII/ECOG 2993). *Blood* 2009; 114:5136-45.

[40] Gersen SL, Keagle MB (eds): The principles of clinical cytogenetics. Humana Press, Second Edition, 2005.

[41] Nguyen K, Devidas M, Cheng SC, La M, Raetz EA, Carroll WL, et al. Factors influencing survival after relapse from acute lymphoblastic leukemia: a Children's Oncology Group study. *Leukemia* 2008; 22:2142-50.

[42] Zhang Y, Le Beau MM (2015). Cytogenetics and molecular genetics in acute lymphoblastic leukemia. [http://www.uptodate.com](http://www.uptodate.com)

[43] Hunger SP, Mullighan CG. Redefining ALL classification: toward detecting high-risk ALL and implementing precision medicine. *Blood* 2015; 125:3977-87.

[44] Ma X, Edmonson M, Yergeau D, Muzny DM, Hampton OA, Rusch M, et al. Rise and fall of subclones from diagnosis to relapse in pediatric B-acute lymphoblastic leukemia. *Nat Commun* 2015; 6:6604

[45] Moorman AV, Enshaei A, Schwab C, Wade R, Chilton L, Elliott A, et al. A novel integrated cytogenetic and genomic classification refines risk stratification in pediatric acute lymphoblastic leukemia. *Blood* 2014; 124:1434-44.