
Sociodemographic and Birth Characteristics in Infant Acute Leukemia: A Review

ML Pérez-Saldivar, JM Mejía-Aranguré,
A Rangel-López and A Fajardo Gutiérrez

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/54457>

1. Introduction

Acute leukemias are cancers of the hematopoietic system that involve, in the majority of cases, a malignant transformation of myeloid and lymphoid progenitor cells [1]. Acute leukemias represent the most common type of childhood cancer [2,3]. Acute lymphoblastic leukemia (ALL) has a frequency of five times greater than that of acute myeloblastic leukemia (AML) and is the most common cancer in children, representing 25% to 35% of all childhood cancers [3,4]. The incidence of ALL varies significantly among developed and developing countries. With a reported annual incidence of 20-45 cases per million children, the highest incidence rates are recorded in the Hispanic population in California, Texas and Florida and in Costa Rica and the City of Mexico [4-7]. Despite advances in therapy and improvements in survival, acute leukemia represents one of the main causes of morbidity and mortality in children. The etiology of this disease remains unknown. Only Down syndrome and ionizing radiation have been recognized as risk factors for the development of childhood acute leukemia [8]. However, the risk attributable to these factors is very small. Epidemiological studies exploring different environmental exposures along with advances in cytogenetics and immunophenotyping have identified different subgroups of the disease that must be considered separately. Such is the case of infantile leukemia. Although it is a rare disease in this group, the molecular characteristics and survival are different in infants than in older children, suggesting that the etiology is distinct and most likely involves prenatal factors. The purpose of this chapter is to introduce the reader to a systematic review of the current literature on reported risk factors for childhood acute leukemia (AL). This review reports what is currently known about acute leukemia in infants and future directions.

2. Descriptive epidemiology

Leukemia in infants (<1 year) is an extremely rare disease, and few studies exist that explore the incidence of leukemia in this age group. Parkin et al., reporting incidence rates for this age group in different regions of the world, determined that Mexico recorded the highest incidence rate in children <1 year for the study period, exceeding the rates of the United States, some countries in Latin America, Europe, Asia and Oceania [5]. However, United States, Great Britain, and Australia have some of the highest incidence rates for infantile ALL, with approximately 20-40 cases per million children, whereas countries like Brazil and Cuba have reported rates of approximately 8-12 cases per million children. The Hispanic population of infants in Los Angeles, Japan and Australia has been reported to have the highest AML incidence rates of approximately 10-12 cases per million children. As with ALL, Brazil and Cuba have some of the lowest incidence rates, with approximately 3-5 cases per million children [6].

Descriptive epidemiological studies conducted in Mexico City on acute leukemia and childhood cancer have consistently identified a significant incidence for AL in the infant population. In the 1980-1992 study period, in newborns population ALL occupied the third place as the main type of cancer and the second place in the infant population and after 2 years of age, a very important peak in AL development is observed [9]. For the period 1996-2002, the incidence of AL in infants was 37.5 per 10⁶ children [10,11], and between 1996 and 2006 another study reported an incidence of 33.0 ALL cases per 10⁶ children < 1 year of age [12]. The most recent survey of childhood AL in 2006-2007 in Mexico City reported an incidence rate of ALL and AML of 24.3 and 4.1 per 10⁶ infants, respectively [7].

Epidemiological studies in infants are rare. However, there is a predominance of females in infants with ALL, whereas in children older than 1 year, male are more frequently diagnosed [13]. Because of the young age of presentation of infantile leukemia, studies are focused specifically on pre-conception exposures during pregnancy as potentially relevant exposures that occur *in utero* or shortly before pregnancy. That is, the window of study for the disease in this cohort is very short – approximately 9 months. Therefore, the study of this group can provide essential information not only for this group but also for the development of childhood AL [14,15]. The epidemiological studies have evaluated maternal exposure during pregnancy to different risk factors that could be associated with the development of leukemia in infants. These studies are presented in table 1 and include the publication of epidemiological studies in the last 12 years in the infant population and its association with AL. Although the studies are interesting and provide important information, some studies have failed to find significant associations because they have some methodological limitations, such as sample size (small number of exposed individuals among subgroups) or incomplete and biased exposure assessment (not validated). In some cases they have a low response rates between cases and controls. It is important to consider these aspects for future association studies. Despite these limitations, these studies provide an important contribution to the limited amount of existing studies linking infants with AL and risk factors.

Variables studied	Study design	Cases analyzed	OR (95% CI)	Conclusions	Author and year				
Maternal exposure to household chemicals	Case-control	264 ALL	Petroleum products Any	Gestational exposure to petroleum products was associated with infant leukemia, particularly AML and MLL-	Slater et al., 2011[23]				
		172 AML	ALL OR 1.56 (0.90-2.70); AML OR 2.33 (1.30-4.18); MLL+ OR 1.38 (0.77-2.48)						
		7 Other	Month before pregnancy ALL OR 1.31 (0.71-2.41); AML OR 1.42 (0.71-2.83); MLL+ OR 1.14 (0.58-2.21) During pregnancy ALL OR 1.60 (0.90-2.83); AML OR 2.54 (1.40-4.62); MLL- 2.69 (1.47-4.93)						
Analgesic use during pregnancy	Case-control	262 ALL	Before knowledge pregnancy Any use	Analgesic use during pregnancy was not significantly associated with the risk of infant leukemia.	Ognjanovic et al., 2011[24]				
		172 AML	Aspirin ALL OR 1.03 (0.58-1.85) AML OR 0.55 (0.24-1.26) Non-aspirin non-steroidal anti-inflammatory drugs (NSAID) ALL OR 1.15 (0.80-1.67) AML OR 0.60 (0.37-0.97) Acetaminophen ALL OR 1.16 (0.80-1.68) AML OR 0.66 (0.43-1.01) After knowledge pregnancy Any use Aspirin ALL OR 1.21 (0.48-3.05) AML OR 0.96 (0.32-2.92) NSAID ALL OR 1.33 (0.75-2.37) AML OR 0.81 (0.36-1.83) Acetaminophen ALL OR 1.03 (0.70-1.53) AML OR 0.79 (0.50-1.24)						
		264 ALL	During pregnancy						
		172 AML	Cigarette use						
		7 Other	OR 0.80 (0.52-1.24) ALL OR 0.87 (0.54-1.40)						
		Maternal prenatal cigarette, alcohol and illicit drug use	Case-control			264 ALL	During pregnancy	Cigarette smoking was not associated with childhood leukemia; alcohol and illicit drug use were not consistent with prior reports.	Slater et al., 2011[25]

Variables studied	Study design	Cases analyzed	OR (95% CI)	Conclusions	Author and year
			AML OR 0.74 (0.40-1.35)		
			Alcohol use		
			OR 0.64 (0.43-0.94)		
			ALL OR 0.64 (0.43-0.94)		
			Illicit drug use		
			OR 0.69 (0.40-1.18)		
			ALL OR 0.84 (0.47-1.51)		
			AML OR 0.52 (0.23-1.16)		
Maternal vitamin and iron supplementation	Case-control	264 ALL 172 AML	Prenatal Vitamins OR 0.79 (0.44-1.42) ALL OR 0.63 (0.34-1.18) AML OR 1.20 (0.53-2.75) Iron supplements OR 1.07 (0.75-1.52) ALL OR 1.22 (0.82-1.80) AML OR 0.82 (0.51-1.33) Periconceptional Vitamins OR 0.89 (0.64-1.24) ALL OR 0.77 (0.54-1.11) AML OR 1.05 (0.68-1.61) Iron supplements OR 1.23 (0.63-2.38) ALL OR 1.30 (0.62-2.72) AML OR 0.77 (0.46-1.27) During pregnancy Vitamins OR 0.78 (0.48-1.28) ALL OR 0.66 (0.39-1.11) AML OR 1.05 (0.55-2.04) Iron supplements OR 1.06 (0.74-1.53)	The authors did not observe a prenatal vitamin-infant leukemia association.	Linabery et al., 2010 [26]
Continued...					

Variables studied	Study design	Cases analyzed	OR (95% CI)	Conclusions	Author and year
			ALL OR 1.22 (0.81-1.84)		
			AML OR 0.77 (0.46-1.27)		
Congenital abnormalities	Case-control	264 ALL 172 AML 7 Other	Congenital abnormality (CA) OR 1.2 (0.8-1.9) Birthmarks OR 1.3 (0.7-2.4) Urogenital abnormalities OR 0.7 (0.2-2.0) Other CA OR 1.4 (0.7-2.8)	The authors did not find evidence for a link between CAs and infant leukemia	Johnson et al., 2010 [27]
Parental infertility and infertility treatment	Case-control	264 ALL 172 AML	Women not trying to conceive OR 1.62 (1.01-2.59) ALL OR 2.50 (1.36-4.61) AML OR 1.17 (0.61-2.22) Women with ≥ 1 year of trying OR 0.99 (0.47-2.07) ALL OR 2.01 (0.85-4.78) AML 0.35 (0.09-1.27)	There were no positive associations between parental infertility or infertility treatment and infant leukemia.	Puumala et al., 2010 [28]
Dipyrene	Case-control	132 Acute leukemia	N-Acetyltransferase 2 (NAT2) dipyrene during pregnancy OR 5.19 (1.86-14.5)	NAT2 slow-acetylation profiles associated with infant leukemia & dipyrene	Zanrosso et al., 2010 [29]
Birth weight	Case-control	148 ALL 53 AML	Birth weight >3999 g OR 1.59 (0.79-3.17) ALL OR 2.28 (1.08-4.75) MLL+ OR 2.68 (0.99-7.15)	The results suggest that high birth weight is associated with an increased risk of infant leukemia.	Koifman et al., 2008 [30]
Birth characteristics and maternal reproductive history	Case-control	149 ALL 91 AML	Birth weight ≥ 4000 g OR 1.09 (0.67-1.79) Gestational age <37 weeks OR 0.74 (0.32-1.70) Birth order 2 nd OR 0.60 (0.40-0.91) Maternal age ≥ 35 years OR 0.75 (0.46-1.23)	Maternal history of fetal loss and other birth characteristics were not related to infant leukemia.	Spector et al., 2007 [31]

Variables studied	Study design	Cases analyzed	OR (95% CI)	Conclusions	Author and year
			Prior fetal loss Any OR 1.04 (0.70-1.55)		
			Pre-pregnancy BMI 25-29.9 OR 1.61 (1.04-2.48)		
			Weight gain during pregnancy (kg)>18.14 OR 1.50 (0.84-2.68)		
Maternal anemia	Case-control	178 Acute leukemia	Anemia during pregnancy (<11 g dl ⁻¹) OR 0.93 (0.57-1.53) ALL OR 1.14 (0.65-2.01) AML OR 0.67 (0.32-1.37) ALL/MLL+ OR 0.98 (0.50-1.91) AML/MLL- OR 0.57 (0.16-2.07)	The authors did not find evidence for an increased risk of leukemia in the offspring of mothers with hemoglobin <11 g dl ⁻¹ during pregnancy.	Peters et al., 2006 [32]
Maternal illicit drugs, pain medication, vitamins/iron supplement, folic acid, hormones, abortive drugs, herbal infusions, pesticides during pregnancy	Case-control	202 Acute leukemia	Tobacco ORa 0.89 (0.63-1.25) Marijuana ORa 0.87 (0.63-1.20) Dipyron ORa 1.45 (1.02-2.06) Amoxicillin ORa 0.88 (0.63-1.25) Folic acid ORa 1.22 (0.73-2.05) Metronidazole ORa 1.39 (0.82-2.34), Miso-prostol ORa 1.23 (0.38-4.02) Hormones ORa 8.76 (2.85-26.93) Herbal infusions ORa 1.93 (0.49-7.58) Pesticides ORa 2.18 (1.53-2.13) Hormones intake: Preconception OR 2.26 (1.21-4.21); MLL+ OR 3.34 (1.51-7.36) 1st trimester OR 11.35 (3.20-40.20); MLL+ OR 10.57 (2.33-47.91) 2 nd trimester OR 4.49 (1.07-18.87); MLL+ OR 2.62 (0.15-17.56) 3 rd trimester OR 2.32 (0.60-8.98); MLL+ 1.02 (0.10-9.93)	A statistically significant association between the maternal use of hormones during pregnancy and infant leukemia.	Pombo-de Oliveira et al., 2006 [33]
Maternal diet (DNA topoisomerase II	Case-control	149 ALL 91 AML	DNAt2 inhibitor with MLL+ Quartile 4 OR 0.7 (0.4-1.5)	Maternal consumption of vegetables and fruits were associated	Spector et al., 2005 [34]

Variables studied	Study design	Cases analyzed	OR (95% CI)	Conclusions	Author and year
inhibitor)			ALL OR 0.5 (0.2-1.1) AML OR 3.2 (0.9-11.9) Vegetable and fruits plus index Quartile 4 OR 0.6 (0.3-1.1) ALL OR 0.5 (0.2-0.9) AML OR 1.1 (0.4-2.9)	with a decreased risk of infant leukemia, particularly MLL+. DNAt2 inhibitors increase the risk of AML (MLL+).	
Maternal smoking, alcohol, DNA damaging drugs, herbal medicines, pesticides, Dipyrrone, insecticides	Case-control	49 ALL (19 MLL+) 74 AML (29 MLL+) 13 Other (2 MLL+)	Smoking ALL OR 1.59 (0.82-3.07); AML OR 1.33 (0.63-2.80); MLL+ OR 0.98 (0.46-2.09) Alcohol ALL OR 0.63 (0.25-1.60); AML OR 1.92 (0.90-4.10); MLL+ OR 0.74 (0.29-1.90) DNA Damaging drugs ALL OR 1.78 (0.95-3.34); AML OR 2.28 (1.10-4.71); MLL+ OR 2.31 (1.06-5.06) Herbal medicines ALL OR 4.45 (2.06-9.63); AML OR 2.09 (0.89-4.92); MLL+ OR 3.00 (1.38-6.54) Maternal Pesticide ALL OR 2.53 (0.71-8.97); AML OR 5.08(1.84-14.04); MLL+ OR 4.96 (1.71-14.43) Dipyrrone ALL OR 3.13 (1.02-9.57); AML OR 3.01 (0.93-9.79); MLL+ OR 5.84 (2.09-16.30) Insecticides ALL OR 4.30 (0.66-28.08); AML OR 7.82 (1.73-35.39); MLL+ OR 9.68 (2.11-44.40)	The data suggest that specific chemical exposures of the fetus during pregnancy may cause MLL gene fusions.	Alexander et al., 2001 [35]

Table 1. Risk factors for infant leukemia studied in the last 12 years.

3. Clinical characteristics

Infants with leukemia possess different molecular genetics features, immunophenotypes and cytogenetic characteristics with respect to older children. Infants with ALL have a very high leukocyte count (hyperleukocytosis); the median of leukocyte count in infants with ALL was

recorded as 100×10^9 L. Infants with ALL also often exhibit hepatosplenomegaly, widened mediastinum, and compromise of the central nervous system (CNS) in approximately 15% of cases. In addition, 13% of male infants exhibit infiltrated testes [16,17]. The ratio ALL/AML in infants is approximately 1.5-2.0, and the M4 or M5 morphology predominates in infants diagnosed with AML [5,18,19].

A significant proportion of infants diagnosed with ALL are characterized by a very immature precursor B-lineage ALL – pro B CD-10. The mature B-lineage ALL is very rare and only 4% of cases are of T-lineage [13]. The leukemic cells of infants with ALL express myeloid antigens, which may indicate that this type of leukemia is generated in immature precursor cells that have no lymphoid differentiation [17]. Unlike older children diagnosed with ALL, with a 5-year survival rate of 80%, infants with leukemia have a very poor 5-year survival rate of 50% or less. The 5-year survival rate for infants with AML is 40%, similar to that reported in older children [20-22].

4. Genetic characteristics in infants

Both ALL and AML in infants are frequently associated with abnormalities (genetic rearrangements) involving the Mixed Lineage Leukemia (MLL) gene, also called Htrx, ALL-1 or HRX, which is located on chromosome 11 band q23 [36-38]. This gene is fused promiscuously with different pairs of chromosomes; up to 70 partners have been reported in human leukemia [39]. The most common fusion partners include chromosome 4, reported in 50% of cases; chromosome 11, with a frequency of 20%; and chromosome 9, present in 10% of cases. Fusions of chromosome 9 are presented in older infants, unlike fusions of chromosomes 4 or 11 [40,41]. The ENL chromosome has also been found fused with MLL, although at a lower frequency [38]. Infants with the MLL gene have a very poor prognosis compared with older children with the disease [13,42,43].

MLL translocations are present in 75-85% of ALL infants less than 1 year and in 60% of infant AML cases. MLL translocations are found in older children and are reported in 5% of cases of childhood AL and 85% of leukemias secondary to treatment with topoisomerase II inhibitors, which are usually AMLs [37,42,44,45]. This last frequency is very important because it has implications for the etiology of leukemia in infants.

5. Structure of the MLL gene

The MLL gene is located on chromosome 11q23 just after the repressor domain. The MLL gene is 90 kb, consists of 38 exons, and produces a 12-kb mRNA that encodes a 430-kDa protein of 3969 amino acids in a complex structure. This protein is widely expressed in the developing embryo, where it functions as a regulator of nuclear transcription. In adult tissues, the protein is only minimally expressed [38,41,46,47].

The MLL protein is normally cleaved in the cytoplasm by caspase 1 at amino acids 2666 (cleavable site 1 or CS1) and 2718 (cleavable site 2 or CS2), generating two subunits: the 300-kDa MLL-N and the 180-kDa MLL-C. MLL functions to acetylate, deacetylate and methylate the histones of nucleosomes [40,46]. The mature protein contains a 8.3-kb breakpoint cluster region between exons 5 and 11, and multiple protein domains have been identified: AT hooks, a DNA methyltransferase domain (transcriptional repression domain, TRD), a Plant homology domain (PHD), a transcription activator domain (TA) and Su (var) 3-9 enhancer of zeste trithorax (SET) domain [38,47,48].

MLL gene alterations include deletions, duplications, inversions and reciprocal translocations. In reciprocal translocations, the fusion proteins are generated by interactions with the C-termini of other genes to replace the transcriptional repression and nuclear signaling domains located at the N-terminus of the MLL protein [49,50].

These fusion proteins have been postulated to be involved in leukemogenesis by increasing the expression of the HOXA9 gene during embryo development. The HOXA9 gene encodes a transcription factor, and the increased expression of this gene could represent a critical mechanism for MLL-related leukemia [46,49,51]. Another mechanism by which these fusion proteins promote leukemia is to increase the expression of FLT3 tyrosine kinase [41,52].

6. Prenatal origin

Numerous molecular biology studies have been conducted in twins with blood samples collected at birth from newborns (Guthrie cards) and with blood samples from the umbilical cord to detect inborn metabolic problems and other problems that could occur in newborns. Neonatal blood samples are stored, and thereafter the samples of a child with a diagnosis of leukemia are examined to understand the patient's genetic abnormalities at birth. These abnormalities are compared with those reported in the diagnosis of the patient. In a large proportion of neonatal blood samples, studies have concluded that the leukemia likely started *in utero* during fetal hematopoiesis, although this is not true for all chromosomal abnormalities [14,53,54].

Monozygotic and dizygotic twins have also been studied to determine the heritable fraction of childhood leukemia. More than 50% of twins share a placenta (monozygotic), which allows blood exchange. In these cases, it is likely that if one of the twins had a leukemic clone, it may have an intraplacental metastasis through which the clone could be transmitted to the other twin [37,53]. This hypothesis has been demonstrated through studies in twins with leukemia using translocation markers for unique genetic breakpoints, especially in TEL-AML1 and MLL rearrangements [14,53-55].

In twin infants with a diagnosis of leukemia, the concordance rate was approximately 100% among those twins who shared the placenta [53]. An explanation for this is that the MLL gene is sufficient to cause leukemia, which could happen if the protein has an overall effect on the structure of chromatin or on the stability of gene expression [37,56]. It is likely that the effect

of the MLL gene in DNA repair or cell cycle regulation facilitates additional genetic changes caused by continuous exposure to genotoxic chemicals *in utero* [14]. However, some authors have noted that the MLL gene is not sufficient to generate leukemogenesis and that additional secondary genetic events are necessary in the development of the disease [57,58]. More so when it has reported the presence of this rearrangement in children over 1 year of age which raises the possibility that the relation of this rearrangement to the development of ALL is similar to that of the TEL-AML1 rearrangement; that is, it is an essential cause, but it is indispensable that another environmental factor be involved in order for children with this rearrangement (acquired at birth or not) to develop the disease [59].

Unlike infant leukemias, acute leukemias in older children exhibit a concordance rate between identical twins who share the same placenta of only 10%. This finding, together with transgenic models, indicates that post-natal events are necessary to produce sufficient genetic changes to develop leukemia. This finding explains why leukemia in infants is a different entity than that of older children, and attention must be paid to transplacental exposure *in utero* during embryonic development and fetal hematopoiesis [37,60].

7. Enzyme DNA topoisomerase II

The function of the enzyme DNA topoisomerase II (DNAt2) is to relax the DNA strands that are tightened and knotted during cell replication [61]. DNAt2 generates a break in the double strands of DNA that are then re-sealed, causing a relaxation of the DNA. Some drugs used in the treatment of leukemia, such as the epidofilotoxins and anthracyclines, have apoptotic effects by inhibiting DNAt2. These drugs interfere with the normal function of DNAt2 by stabilizing the break-cleavable complex, which is the DNAt2 enzyme complex responsible for breaking the double-stranded DNA, slowing the ligation of the strands and leaving free the single-stranded DNA ends that can lead to chromosomal abnormalities. These chromosomal abnormalities have been observed in leukemias secondary to the treatment of epidofilotoxins and anthracyclines in children and adults [62,63], and patients treated with these drugs have a greater likelihood of developing secondary AML with MLL translocations [64]. Several chemical compounds are able to inhibit DNAt2, including chemotherapeutic drugs containing quinone substances [65,66]. The enzyme NAD(P)h:quinone oxidoreductase 1 (NQO1) is involved in the metabolism of chemicals that inhibit DNAt2. The functional polymorphism C609T reduces the activity of NQO1 and exhibits a phenotypic dose-gene effect [67,68]. Several studies have assessed the associated risk of possessing the variant allele T at locus NQO1 C609T in patients with childhood AL and MLL rearrangement. The results are mixed; only some studies observed an increased risk with NQO1 C609T in infants with leukemia and MLL [66,69,70].

However, there are other sources of exposure to DNAt2 inhibitors that may increase the risk of acute leukemia in infants [42]. These DNAt2 inhibitors are found in some drugs, substances derived from benzene and naturally in some foods that contain flavonoids [71].

8. Therapy-related secondary leukemias

The growing use of intensive therapies in the treatment of patients with cancer has caused an increase in the incidence of secondary neoplasms. The complexity of anti-cancer treatments makes it difficult to know what agents are more leucemogenous and which act more quickly in the leukemic transformation of the hematopoiesis progenitor cells. The term secondary leukemia is usually employed to indicate both forms of AML evolving from previous myelodysplasia and forms of acute leukemia developing after exposure to environmental or therapeutic toxins or radiation (therapy-related). Secondary leukemias account for 10-30% of all AML. The majority of secondary leukemias resulting from the use of cytotoxic drugs can be divided into two well defined groups depending on whether the patient has received: 1) alkylating agents or 2) drugs binding to the enzyme DNA-topoisomerase II.

Alkylating agents related leukemias are very similar to post myelodysplasia leukemias being characterized frequently by a preleukemic phase, trilineage dysplasia, frequent cytogenetic abnormalities involving chromosomes 5 and 7 and a poor prognosis. Secondary leukemias related to therapy with topoisomerase II inhibitors are not preceded by a preleukemic phase and show frequently balanced translocations involving chromosome 11q23. Among therapy-related leukemias, AML is generally a second neoplasm, thus a predisposition to malignancy, independently from previous chemotherapy, cannot be excluded. It has been mentioned that the incidence of secondary leukemias increases with age [72] and leukemic cells predominantly exhibit a monocytic or myelomonocytic phenotype and balanced chromosomal translocations including 11q23 and 21q22 rearrangements or abnormalities such as t(15;17)(q22;q12) and inv(16)(p13q22). A history of previous treatment with topoisomerase-II-inhibitors is common in these individuals. However, as many patients have received multiple lines of treatment including several classes of chemotherapy compounds, both structural and balanced chromosomal aberrations are frequently observed in the leukaemic clone. The World Health Organization (WHO) has therefore abandoned its former classification into alkylating agent or topoisomerase-II-inhibitor associated therapy-related disease. As a conservative estimate, about 10% of cases of AML and myelodysplastic syndrome (MDS) are therapy related [73].

Alkylating agents

Alkylating agents were the first chemotherapeutic compounds to be associated with leukaemia development after successful treatment of solid and haematological cancers [74-78]. They comprise a large group of anti-cancer drugs with clinical application across almost all cancer types. Alkylating agents induce DNA damage by transferring alkyl groups – such as -CH₃ or -CH₂-CH₃ – to oxygen or nitrogen atoms of DNA bases, resulting in highly mutagenic DNA base lesions, such as O₆-methylguanine and N₃-methylcytosine [79-82].

Drugs binding to the enzyme DNA-topoisomerase II (topoisomerase inhibitors)

While alkylating agents associated with therapy-related myeloid neoplasms (t-MNs) are characterized by a complex karyotype often featuring partial or complete loss of chromo-

somes 5 and/or 7, exposure to topoisomerase inhibitors leads to the development of leukaemias with balanced translocations involving MLL at 11q23, RUNX1 at 21q22 and RARA at 17q21 [83-85]. MLL fusion genes are also common in secondary acute myeloid leukemia (usually French-American-British (FAB) M4/M5) associated with prior therapeutic exposure to topoisomerase-II inhibiting anthracyclines or epipodophyllotoxins [62]. These observations have prompted speculation on possible exposure to topoisomerase-II inhibiting substances during pregnancy that might give rise to MLL fusions during fetal hematopoiesis [86].

DNA topoisomerases are critical enzymes responsible for unknotting and relaxing supercoiled DNA, thus allowing DNA replication to occur. To relax supercoiled DNA, topoisomerases bind covalently to the DNA strand and create transient single (type I topoisomerases) and DSBs (type II topoisomerases). These DNA strand breaks are readily religated after topoisomerases are released from the DNA [87]. As these ubiquitous enzymes are essential to cell survival, DNA topoisomerases have become a valuable target for several cytostatic drugs, such as epipodophyllotoxins and anthracyclines. Topoisomerase inhibitors block the release of topoisomerases from cleaved DNA, preventing religation of the DNA strands [88]. Thus, topoisomerase inhibitors lead to the generation of permanent DNA DSBs that trigger DSB-induced apoptosis. However, persistent DNA DSBs are also highly mutagenic and can result in chromosomal deletions, insertions, inversions and translocations, all of which are characteristic of the leukaemic cell clone in t-MNs. The exact molecular effects of these inhibitors on the acquisition of chromosomal aberrations and the development of this t-MN subtype have recently been reviewed in detail [89].

Dexrazoxane – a bisdioxopiperazine iron chelator used to reduce cardiopulmonary toxicity in patients treated with anthracyclines – also interferes with topoisomerase II in its dimerized state by bridging and stabilizing the ATPase region. In a randomized phase III study in paediatric patients treated with chemo- and radiotherapy for Hodgkin's disease, dexrazoxane was associated with a cumulative incidence of MDS/AML of 2.5% - 1.0% as compared with 0.85% - 0.6% for the non-dexrazoxane group ($P = 0.16$). This trend towards an increased risk of secondary neoplasms associated with dexrazoxane was subsequently confirmed in patients with childhood acute lymphoblastic leukaemia [90]. In children cured of ALL, the risk of a therapy-related acute myeloid leukaemia (t-AML) has been evaluated in different series to be between 3.8% at 6 years and 5.9% at 4 years [64,91-96]. The risk of secondary acute myeloid leukemia (sAML) was higher among ALL children who received a high cumulative dose of epipodophyllotoxins (>4,000 mg/m²) and prolonged epipodophyllotoxin therapy in weekly or twice-weekly doses. In adults a GIMEMA study demonstrated a low incidence of t-AML, which could be explained by the lower doses of epipodophyllotoxins administered in the various therapeutic approaches used for the treatment of adult ALL [96].

MLL gene has been involved in secondary leukemias treatment, mainly of the type AML in patients treated with inhibitors of topoisomerase II as a primary cancer treatment. It has been postulated the presence of similar mechanisms for Leukemia in infants whose mothers had exposure to native II topoisomerases [97].

9. Diet and infant leukemia

Studies on environmental risk factors related to AL with MLL rearrangements have focused on maternal diet effects on *in utero* exposure. Dietary compounds exist that can inhibit the function of DNAt2, thereby posing a potential leukemogenesis threat in infants [43,64]. DNAt2 is critical in cellular processes such as replication, where transiently breaks down and subsequently seals the DNA strand [37]. DNAt2 is able to rapidly increase its activity during cell division [98]. Diet is a natural source of DNAt2 inhibitors, including flavonoids [71,99].

Flavonoids are a very large group of Polyphenolic compounds found in foods of plant origin. Polyphenols are involved in the development and reproduction of plants, and they provide resistance against pathogens, plagues and protect crops from diseases that inhibit the germination of their seeds [100]. Flavonoids are divided into 6 subgroups: flavones, flavanols, flavanones, catechins, anthocyanidins and isoflavones [71] (see table 2); in the last decade, more than 5000 subclasses have been identified [101,102]. Importantly, several biological effects have been observed in *in vitro* studies of flavonoids, including its antioxidant activity, modulation of enzyme activity, inhibition cell proliferation and use as antibiotics, anti-allergy, anti-diarrhea, anti-ulcer and anti-inflammatory agents [103-106].

The properties attributed to flavonoids have prompted increased interest in alternative medicine and herbal remedies. Numerous foods, beverages and supplements exist on the market that contains high levels of flavonoids. Therefore, it is likely that the amount of flavonoids in the typical diet is presently increasing [102].

The study the consumption of DNAt2 inhibitors during pregnancy in women who have children who develop leukemia is founded on the idea that foods containing natural DNAt2 inhibitors cause damage to DNA, much in the same way as the epidofilotoxinas. There have been several bioavailability studies on flavonoids that have demonstrated that there are differences in their absorption, depending on the source of food. The accumulation of these compounds in blood has been measured [107]. Some studies in animals and *in vitro* have demonstrated that flavonoid DNAt2 inhibitors are capable of crossing the placenta and damaging DNA [108,109]. One study reported the flavonoids can cause a break in the MLL gene in hematopoietic progenitor cells, which was reversible when the exposure was removed. The site of disruption caused by the flavonoids was co-localized with the same site associated with the epidofilotoxinas [37,60,99]. All of these findings provide evidence for epidemiological studies in the pursuit of this association with leukemia in infants.

Studies of maternal diets during pregnancy and their association with childhood AL have been led by Ross JA. [110], who through a case-control study in infants and a questionnaire for maternal exposure to dietary DNAt2 inhibitors and drugs in pregnancy observed a statistically significant association between AML and the medium and high consumption of DNAt2 inhibitors (OR 9.8; 95% confidence interval [CI] 1.1-84.8; OR 10.2; 95% CI 1.1-96.4). However, this study observed no association with ALL. Ross JA intends to continue studying infants with AL and stresses the importance of incorporating molecular markers that could provide more information.

Flavones (Apigenin, luteolin, diosmetin)	Flavonols (Quercetin, myricetin, kaempferol)	Flavanones (Naringenin, hesperidin)	Catechins or Flavanols (Epicatechin, gallic acid)	Anthocyanidins (Pelargonidin, malvidin, cyanidin)	Isoflavones (Genistein, daidzein)
Parsley	Onions	Citrus foods	Tea	Cherries	Soya beans
Thyme	Kale	Prunes	Apples	Grapes	Legumes
Celery	Broccoli		Cocoa		
Sweet red pepper	Apples				
	Cherries				
	Fennel				
	Sorrel				
	Berries				
	Tea				

Table 2. Major subgroups of flavonoids and food sources.

Later, Jensen CD et al. [111] studied maternal diet and its association with childhood ALL through a food frequency questionnaire, observing a protective effect with the consumption of vegetables, protein and fruits (OR 0.53; 95% CI 0.33-0.85; OR 0.40; 95% CI 0.18-0.90; OR 0.71; 95% CI 0.49-1.04, respectively). In 2005s Spector et al. [34] published the results of a case-control study in infants in which they proposed that exposure to high levels of DNAt2 inhibitors in the diet was associated with the risk of MLL+ leukemia in infants. The authors observed a non-significant association between MLL+ AML but a trend among the second and fourth quartiles of DNAt2 inhibitor consumption (OR 1.9; 95% CI 0.5-7.0; OR 2.1; 95% CI 0.6-7.7; OR 3.2; 95% CI 0.9-11.9). A non-significant inverse association was observed with MLL+ ALL. Another study conducted by Petridou et al. [112] in children ≤ 4 years old diagnosed with ALL asked about the mothers' diets during pregnancy and found that the consumption of fruits (OR 0.72; 95% CI 0.57-0.91), vegetables (OR 0.76; 95% CI 0.60-0.9) and fish/seafood (OR 0.72; 95% CI 0.59-0.89) decreased the risk for ALL. However, the consumption of sugar/honey and meat/derivatives increased the risk for ALL (OR 1.32; 95% CI 1.05-1.67; OR 1.25; 95% CI 1.00-1.57, respectively). The most recent study on maternal diet and childhood ALL was undertaken by Kwan ML et al., [113] who applied a food-frequency questionnaire about food consumed 1 year before pregnancy. The results of their study indicate that the risk for ALL was inversely associated with maternal consumption of vegetables (OR 0.65; 95% CI 0.50-0.84), sources of protein (OR 0.55; 95% CI 0.32-0.96), fruits (OR 0.81; 95% CI 0.65-1.00) and legume food groups (OR 0.75; 95% CI 0.59-0.95).

Thus far, epidemiological studies have identified the protective effect of fruits and vegetables consumption during pregnancy against infantile ALL. These results are not observed in AML with the exception of the studies of Ross et al., in which the authors identified a positive association between the high intake of DNAt2 inhibitors in foods and AML/MLL+ in infants. These results confirm that AL in children is composed of different subgroups with different disease etiologies [37,42].

The most recent epidemiological study in infants is the one published by the group of Ross et al., [114] with a significant number of cases (374). In this study, the authors describe some of the demographic factors and the MLL gene status in infants with leukemia. They generally reported a higher frequency of females (50.8%), and the most common ethnic group was Caucasian (70%), followed by Hispanics (27.8%). The most frequent age of diagnosis was 4-6 months (27.8%), and 51.5% of cases were MLL+, 33.0% were MLL-, and 15.6% were undetermined. The chromosome most frequently found fused to the MLL gene was chromosome 4 [t(4;11)]. Interestingly, the black ethnic group had a lower risk of MLL+ leukemia (OR 0.27; 95% CI 0.11-0.70), and a protective effect was observed in infants 10-12 months old (OR 0.39; 95% CI 0.21-0.73). Cases of ALL and t(9;11) were diagnosed at older ages than cases with t(4;11) or other translocations ($P = 0.01$). These findings provide important information of the biology of the disease. Undoubtedly, this study necessitates future publications to report socio-economic data, exposure to DNAt2 inhibitors and other maternal risk factors during pregnancy and their association with leukemia in infants.

Another study is currently being conducted by our research group in Mexico City. This study emerged because Mexico City has a high incidence rate of acute leukemia in infants. In addition, a previous study observed that the frequency of MLL/AF4 rearrangements in patients diagnosed with childhood leukemia was high [59]. This is an epidemiological case-control study in infants; the objectives are to identify the relationship between *in utero* exposure to environmental factors inhibiting DNAt2 that are present in the maternal diet during pregnancy, including drugs and benzene derivatives. Biological samples of patients are being analyzed to detect the MLL/AF4 gene rearrangement in infants. In addition, we will know the frequencies of exposure to environmental factors that inhibit DNAt2 in the mothers of infants with MLL+ AL. Nine hospitals that belong to the most important public health institutions in our country are participating in this study. These hospitals diagnose and treat 97.5% of all leukemia cases in Mexico City [7]. The results obtained from this study will be very relevant to one of the cities with the highest incidence rates for childhood AL.

10. Future directions

Due to the findings reported thus far, the authors have recommended carrying out studies in infants that are focused on different biological strata like female/male ratios because hormonal differences could indicate an important predisposition to the presence of MLL+ rearrangement. Another suggestion is to study different ethnic groups, where the genetic involvement can provide substantial information about this cohort [112]. For future studies, one must

consider the importance of a big sample size, questionnaires validated and, when possible to incorporate biological or environmental samples that enhance the exposure information, such as pre-diagnostic biological samples. In addition to considering collaborative studies between epidemiologists, clinicians, biologists, and others will enrich the results of these studies.

11. Conclusion

There is sufficient evidence to indicate that acute leukemia in infants is initiated *in utero* with MLL rearrangements. Epidemiological studies have demonstrated that flavonoids and some benzene derivatives present in the maternal diet during pregnancy can act as inhibitors of DNAt2 and are associated with the development of AML in infants with MLL+. This association has not been observed for ALL in infants, although an inverse association with the consumption of vegetables and fruits has been reported for ALL. Is a priority to identify environmental or other types of factors that could be contributing to the greater presence of this type of rearrangement during pregnancy and their association with leukemia in infants.

Acknowledgements

Supported by CONSEJO NACIONAL DE CIENCIA Y TECNOLOGIA (CONACYT), Grant 2010-1-141026, IMSS/FIS/PROT 895; CB-2007-1-83949; 2007-1-18-71223, IMSS/FIS/PROT 056.

Author details

ML Pérez-Saldivar^{1*}, JM Mejía-Arangur², A Rangel-López² and A Fajardo Gutiérrez¹

*Address all correspondence to: maria_luisa_2000_mx@yahoo.com

1 Unidad de Investigación en Epidemiología Clínica, Unidad Médica de Alta Especialidad UMAE Hospital de Pediatría, Centro Médico Nacional (CMN) Siglo XXI, México

2 Coordinación de Investigación en Salud, Instituto Mexicano de Seguridad Social (IMSS), México D.F., México

References

- [1] Greaves, M. (1996). The New biology of leukemia, In: Henderson ES, Lister TA, Greaves MF. (Eds) Leukemia. Philadelphia: WB Saunders. , 34-45.
- [2] Parkin, D. M. International variation. *Oncogene* (2004). , 23(38), 6329-6340.

- [3] Stiller, C. A. Epidemiology and genetics of childhood cancer. *Oncogene* (2004). , 23(38), 6429-6444.
- [4] Lightfoot, T. J, & Roman, E. Causes of childhood leukaemia and lymphoma. *Toxicology and Applied Pharmacology* (2004). , 199(2), 104-117.
- [5] Parkin, D. M, Stiller, C. A, Draper, G. J, & Bieber, C. A. The international incidence of childhood cancer. *International Journal of Cancer* (1988). , 42(4), 511-520.
- [6] Parkin, D. M, Kramárová, E, Draper, G. J, Masuyer, E, Michaelis, J, & Neglia, J. Qureshi S & Stiller CA (Eds.). *International Incidence of Childhood Cancer: IARC Scientific Publications International Agency for Research on Cancer*; (1998). , 2(144)
- [7] Pérez-saldivar, M. L, Fajardo-gutiérrez, A, Bernáldez-ríos, R, Martínez-avalos, A, Medina-sanson, A, & Espinosa-hernández, L. Flores-Chapa Jde D, Amador-Sánchez R, Peñaloza-González JG, Alvarez-Rodríguez FJ, Bolea-Murga V, Flores-Lujano J, Rodríguez-Zepeda Mdel C, Rivera-Luna R, Dorantes-Acosta EM, Jiménez-Hernández E, Alvarado-Ibarra M, Velázquez-Aviña MM, Torres-Nava JR, Duarte-Rodríguez DA, Paredes-Aguilera R, Del Campo-Martínez Mde L, Cárdenas-Cardos R, Alamilla-Galicia PH, Bekker-Méndez VC, Ortega-Alvarez MC, Mejía-Arangure JM. Childhood acute leukemias are frequent in Mexico City: descriptive epidemiology. *BMC Cancer* (2011).
- [8] Eden, T. Aetiology of childhood leukaemia. *Cancer Treatment Reviews* (2010). , 36(4), 286-297.
- [9] Mejía Aranguré JM, Flores Aguilar H, Juárez Muñoz I, Vázquez Langle J, Games Eternod J, Pérez Saldívar ML, Ortega Alvarez MC, Rendón Macías ME, Gutiérrez AF. Age of onset of different malignant tumors in childhood. *Revista Médica del Instituto Mexicano del Seguro Social* (2005). , 43(1), 25-37.
- [10] Fajardo-gutiérrez, A, Juárez-ocaña, S, González-miranda, G, Palma-padilla, V, Carreón-cruz, R, Ortega-alvárez, M. C, & Mejía-arangure, J. M. Incidence of cancer in children residing in ten jurisdictions of the Mexican Republic: importance of the Cancer registry (a population-based study). *BMC Cancer* (2007).
- [11] Rendón-macías, M. E, Mejía-aranguré, J. M, Juárez-ocaña, S, & Fajardo-gutiérrez, A. Epidemiology of cancer in children under one year of age in Mexico City. *European Journal of Cancer Prevention* (2005). , 14(2), 85-89.
- [12] Bernaldez-rios, R, Ortega-alvarez, M. C, Perez-saldivar, M. L, & Alatorre-medina, N. E. Del Campo-Martinez Mde L, Rodriguez-Zepeda Mdel C, Montero-Ponce I, Franco-Ornelas S, Fernandez-Castillo G, Nuñez-Villegas NN, Taboada-Flores MA, Flores-Lujano J, Argüelles-Sanchez ME, Juarez-Ocaña S, Fajardo-Gutierrez A, Mejia-Arangure JM. The age incidence of childhood B-cell precursor acute lymphoblastic leukemia in Mexico City. *Journal of pediatric hematology/oncology* (2008). , 30(3), 199-203.
- [13] Pieters, R. Biology and treatment of infant leukemias, In: Ching-Hon Pui. (ed.) *Treatment of acute leukemias: New Directions for Clinical Research*. Totowa, New Jersey: Humana Press; (2003). , 61-73.

- [14] Greaves, M. In utero origins of childhood leukaemia. *Early human development* (2005). , 81(1), 123-129.
- [15] Ross, J. A. Environmental and genetic susceptibility to MLL-defined infant leukemia. *Journal of the National Cancer Institute Monographs* (2008).
- [16] Ross, J. A, Davies, S. M, Potter, J. D, & Robison, L. L. Epidemiology of childhood leukemia, with a focus on infants. *Epidemiologic reviews* (1994). , 16(2), 243-272.
- [17] Pieters, R. Infant acute lymphoblastic leukemia: Lessons learned and future directions. *Current hematologic malignancy reports* (2009). , 4(3), 167-174.
- [18] Cimino, G, Rapanotti, M. C, Elia, L, Biondi, A, Fizzotti, M, Testi, A. M, Tosti, S, Croce, C. M, Canaani, E, & Mandelli, F. and Lo Coco F. ALL-1 gene rearrangements in acute myeloid leukemia: association with M4-M5 French-American-British classification subtypes and young age. *Cancer research* (1995). , 55(8), 1625-1628.
- [19] Gurney, J. G, Ross, J. A, Wall, D. A, Bleyer, W. A, Severson, R. K, & Robison, L. L. Infant cancer in the U.S.: histology-specific incidence and trends, 1973 to 1992. *Journal of pediatric hematology/oncology* (1997). , 19(5), 428-432.
- [20] Hilden, J. M, Dinndorf, P. A, Meerbaum, S. O, Sather, H, Villaluna, D, Heerema, N. A, Mcglennen, R, Smith, F. O, Woods, W. G, Salzer, W. L, Johnstone, H. S, & Dreyer, Z. Reaman GH; Children's Oncology Group. Analysis of prognostic factors of acute lymphoblastic leukemia in infants: report on CCG 1953 from the Children's Oncology Group. *Blood* (2006). , 108(2), 441-451.
- [21] Ries LAGEisner MP, Kosary CL, Hankey BF, Miller BA, Clegg L, Mariotto A, Fay MP, Feuer EJ, Edwards BK (eds). SEER Cancer Statistics Review, National Cancer Institute. Bethesda, MD, http://seer.cancer.gov/csr/1975_2000/,(2003). accessed 10 July 2012),, 1975-2000.
- [22] Ries, L. A. G, Smith, M. A, Gurney, J. G, Linet, M, Tamra, T, Young, J. L, & Bunin, G. R. Cancer incidence and survival among children and adolescents: United States SEER Program (1999). , 1975-1995.
- [23] Slater, M. E, Linabery, A. M, Blair, C. K, Spector, L. G, Heerema, N. A, Robison, L. L, & Ross, J. A. Maternal prenatal cigarette, alcohol and illicit drug use and risk of infant leukaemia: a report from the Children's Oncology Group. *Paediatric and perinatal epidemiology* (2011). , 25(6), 559-565.
- [24] Ognjanovic, S, Blair, C, Spector, L. G, Robison, L. L, Roesler, M, & Ross, J. A. Analgesic use during pregnancy and risk of infant leukaemia: a Children's Oncology Group study. *British journal of cancer* (2011). , 104(3), 532-536.
- [25] Slater, M. E, Linabery, A. M, Blair, C. K, Spector, L. G, Heerema, N. A, Robison, L. L, & Ross, J. A. Maternal prenatal cigarette, alcohol and illicit drug use and risk of infant leukaemia: a report from the Children's Oncology Group. *Paediatric and perinatal epidemiology* (2011). , 25(6), 559-565.

- [26] Linabery, A. M, Puumala, S. E, Hilden, J. M, Davies, S. M, Heerema, N. A, & Roesler, M. A. Ross JA; Children's Oncology Group. Maternal vitamin and iron supplementation and risk of infant leukaemia: a report from the Children's Oncology Group. *British journal of cancer* (2010). , 103(11), 1724-1728.
- [27] Johnson, K. J, Roesler, M. A, Linabery, A. M, Hilden, J. M, Davies, S. M, & Ross, J. A. Infant leukemia and congenital abnormalities: a Children's Oncology Group study. *Pediatric blood & cancer* (2010). , 55(1), 95-99.
- [28] Puumala, S. E, Spector, L. G, Wall, M. M, Robison, L. L, Heerema, N. A, Roesler, M. A, & Ross, J. A. Infant leukemia and parental infertility or its treatment: a Children's Oncology Group report. *Human reproduction* (2010). , 25(6), 1561-1568.
- [29] Zanrosso, C. W, Emerenciano, M, Gonçalves, B. A, Faro, A, Koifman, S, & Pombo-de-oliveira, M. S. N-a. c. e. t. y. l. t. r. a. n. s. f. e. r. a. s. e. polymorphisms and susceptibility to infant leukemia with maternal exposure to dipyrone during pregnancy. *Cancer epidemiology, biomarkers & prevention* (2010). , 19(12), 3037-3043.
- [30] Koifman, S. Pombo-de-Oliveira MS; Brazilian Collaborative Study Group of Infant Acute Leukemia. High birth weight as an important risk factor for infant leukemia. *British journal of cancer* (2008). , 98(3), 664-667.
- [31] Spector, L. G, Davies, S. M, Robison, L. L, Hilden, J. M, Roesler, M, & Ross, J. A. Birth characteristics, maternal reproductive history, and the risk of infant leukemia: a report from the Children's Oncology Group. *Cancer epidemiology, biomarkers & prevention* (2007). , 16(1), 128-134.
- [32] Peters, A. M, Blair, C. K, Verneris, M. R, Neglia, J. P, Robison, L. L, Spector, L. G, Reaman, G. H, & Felix, C. A. Ross JA; Children's Oncology Group. Maternal haemoglobin concentration during pregnancy and risk of infant leukaemia: a children's oncology group study. *British journal of cancer* (2006). , 95(9), 1274-1276.
- [33] Pombo-de-oliveira, M. S. Koifman S; Brazilian Collaborative Study Group of Infant Acute Leukemia. Infant acute leukemia and maternal exposures during pregnancy. *Cancer epidemiology, biomarkers & prevention* (2006). , 15(12), 2336-2341.
- [34] Spector, L. G, Xie, Y, Robison, L. L, Heerema, N. A, Hilden, J. M, Lange, B, Felix, C. A, Davies, S. M, Slavin, J, Potter, J. D, Blair, C. K, Reaman, G. H, & Ross, J. A. Maternal diet and infant leukemia: the DNA topoisomerase II inhibitor hypothesis: a report from the children's oncology group. *Cancer epidemiology, biomarkers & prevention* (2005). , 14(3), 651-655.
- [35] Alexander, F. E, Patheal, S. L, Biondi, A, Brandalise, S, Cabrera, M. E, Chan, L. C, Chen, Z, Cimino, G, Cordoba, J. C, Gu, L. J, Hussein, H, Ishii, E, Kamel, A. M, Labra, S, Magalhães, I. Q, Mizutani, S, Petridou, E, De Oliveira, M. P, Yuen, P, Wiemels, J. L, & Greaves, M. F. Transplacental chemical exposure and risk of infant leukemia with MLL gene fusion. *Cancer research* (2001). , 61(6), 2542-2546.

- [36] Brassesco, M. S, Montaldi, A. P, Gras, D. E, Camparoto, M. L, Martinez-rossi, N. M, Scrideli, C. A, Tone, L. G, & Sakamoto-hojo, E. T. Cytogenetic and molecular analysis of MLL rearrangements in acute lymphoblastic leukaemia survivors. *Mutagenesis* (2009). , 24(2), 153-60.
- [37] Greaves, M. F, & Wiemels, J. Origins of chromosome translocations in childhood leukaemia. *Nature reviews Cancer* (2003). , 3(9), 639-649.
- [38] Krivtsov, A. V, & Armstrong, S. A. MLL translocations, histone modifications and leukaemia stem-cell development. *Nature reviews Cancer* (2007). , 7(11), 823-833.
- [39] Meyer, C, Schneider, B, Jakob, S, Strehl, S, Attarbaschi, A, Schnittger, S, Schoch, C, Jansen, M. W, & Van Dongen, J. J. den Boer ML, Pieters R, Ennas MG, Angelucci E, Koehl U, Greil J, Griesinger F, Zur Stadt U, Eckert C, Szczepański T, Niggli FK, Schäfer BW, Kempfski H, Brady HJ, Zuna J, Trka J, Nigro LL, Biondi A, Delabesse E, Macintyre E, Stanulla M, Schrappe M, Haas OA, Burmeister T, Dingermann T, Klingebiel T, Marschalek R. The MLL recombinome of acute leukemias. *Leukemia* (2006). , 20(5), 777-784.
- [40] Daser, A, & Rabbitts, T. H. Extending the repertoire of the mixed-lineage leukemia gene MLL in leukemogenesis. *Genes & development* (2004). , 18(9), 965-974.
- [41] Chowdhury, T, & Brady, H. J. Insights from clinical studies into the role of the MLL gene in infant and childhood leukemia. *Blood cells, molecules & diseases* (2008). , 40(2), 192-199.
- [42] Ross, J. A. Maternal diet and infant leukemia: a role for DNA topoisomerase II inhibitors? *International journal of cancer Supplement* (1998).
- [43] Pui, C. H, Carroll, W. L, Meshinchi, S, & Arceci, R. J. Biology, risk stratification, and therapy of pediatric acute leukemias: an update. *Journal of clinical oncology* (2011). , 29(5), 551-565.
- [44] Ross, J. A. Environmental and genetic susceptibility to MLL-defined infant leukemia. *Journal of the National Cancer Institute Monographs* (2008).
- [45] Brassesco, M. S, Montaldi, A. P, & Sakamoto-hojo, E. T. Preferential induction of MLL(Mixed Lineage Leukemia) rearrangements in human lymphocyte cultures treated with etoposide. *Genetics and molecular biology* (2009). , 32(1), 144-150.
- [46] Slany, R. K. The molecular biology of mixed lineage leukemia. *Haematologica* (2009). , 94(7), 984-993.
- [47] Wiederschain, D, Kawai, H, Shilatifard, A, & Yuan, Z. M. Multiple mixed lineage leukemia (MLL) fusion proteins suppress response to DNA damage. *The Journal of biological chemistry* (2005). , 53.
- [48] Hess, J. L. MLL: a histone methyltransferase disrupted in leukemia. *Trends in molecular medicine* (2004). , 10(10), 500-507.

- [49] Aplan, P. D. Chromosomal translocations involving the MLL gene: molecular mechanisms. *DNA Repair (Amst)* (2006).
- [50] Rubnitz, J. E, Behm, F. G, & Downing, J. R. q23 rearrangements in acute leukemia. *Leukemia* (1996). , 10(1), 74-82.
- [51] Bach, C, Buhl, S, Mueller, D, García-cuellar, M. P, Maethner, E, & Slany, R. K. Leukemogenic transformation by HOXA cluster genes. *Blood* (2010). , 115(14), 2910-2918.
- [52] Armstrong, S. A, Kung, A. L, Mabon, M. E, Silverman, L. B, & Stam, R. W. Den Boer ML, Pieters R, Kersey JH, Sallan SE, Fletcher JA, Golub TR, Griffin JD, Korsmeyer SJ. Inhibition of FLT3 in MLL. Validation of a therapeutic target identified by gene expression based classification. *Cancer Cell* (2003). , 3(2), 173-183.
- [53] Greaves, M. F, Maia, A. T, Wiemels, J. L, & Ford, A. M. Leukemia in twins: lessons in natural history. *Blood* (2003). , 102(7), 2321-2333.
- [54] Maia, A. T, Van Der Velden, V. H, Harrison, C. J, Szczepanski, T, Williams, M. D, Griffiths, M. J, Van Dongen, J. J, & Greaves, M. F. Prenatal origin of hyperdiploid acute lymphoblastic leukemia in identical twins. *Leukemia* (2003). , 17(11), 2202-2206.
- [55] Hong, D, Gupta, R, Ancliff, P, Atzberger, A, Brown, J, Soneji, S, Green, J, Colman, S, Piacibello, W, Buckle, V, Tsuzuki, S, Greaves, M, & Enver, T. Initiating and cancer-propagating cells in TEL-AML1-associated childhood leukemia. *Science* (2008). , 319(5861), 336-339.
- [56] Ayton, P. M, & Cleary, M. L. Molecular mechanisms of leukemogenesis mediated by MLL fusion proteins. *Oncogene* (2001). , 20(40), 5695-5707.
- [57] Bueno, C, Montes, R, Catalina, P, Rodríguez, R, & Menendez, P. Insights into the cellular origin and etiology of the infant pro-B acute lymphoblastic leukemia with MLL-AF4 rearrangement. *Leukemia* (2011). , 25(3), 400-410.
- [58] Eguchi, M, Eguchi-ishimae, M, & Greaves, M. Molecular pathogenesis of MLL-associated leukemias. *International journal of hematology* (2005). , 82(1), 9-20.
- [59] Daniel-cravioto, A, Gonzalez-bonilla, C. R, Mejia-arangure, J. M, Perez-saldivar, M. L, Fajardo-gutierrez, A, Jimenez-hernandez, E, Hernandez-serrano, M, & Bekker-mendez, V. C. Genetic rearrangement MLL/AF4 is most frequent in children with acute lymphoblastic leukemias in Mexico City. *Leukemia & lymphoma* (2009). , 50(8), 1352-1360.
- [60] Ford, A. M, Ridge, S. A, Cabrera, M. E, Mahmoud, H, Steel, C. M, Chan, L. C, & Greaves, M. In utero rearrangements in the trithorax-related oncogene in infant leukaemias. *Nature* (1993). , 363(6427), 358-360.
- [61] Wang, J. C. DNA topoisomerases. *Annual review of biochemistry* (1996).
- [62] Felix, C. A. Secondary leukemias induced by topoisomerase-targeted drugs. *Biochimica et biophysica acta* (1998).

- [63] Rowley, J. D, & Olney, H. J. International workshop on the relationship of prior therapy to balanced chromosome aberrations in therapy-related myelodysplastic syndromes and acute leukemia: overview report. *Genes Chromosomes Cancer* (2002). , 33(4), 331-345.
- [64] Pui, C. H, Behm, F. G, Raimondi, S. C, Dodge, R. K, George, S. L, & Rivera, G. K. Mirro J Jr, Kalwinsky DK, Dahl GV, Murphy SB. Secondary acute myeloid leukemia in children treated for acute lymphoid leukemia. *The New England journal of medicine* (1989). , 321(3), 136-142.
- [65] Chen, H, & Eastmond, D. A. Topoisomerase inhibition by phenolic metabolites: a potential mechanism for benzene's clastogenic effects. *Carcinogenesis* (1995). , 16(10), 2301-2307.
- [66] Wiemels, J, Wiencke, J. K, Varykoni, A, & Smith, M. T. Modulation of the toxicity and macromolecular binding of benzene metabolites by NAD(P)H:Quinone oxidoreductase in transfected HL-60 cells. *Chemical research in toxicology* (1999). , 12(6), 467-475.
- [67] Siegel, D, McGuinness, S. M, Winski, S. L, & Ross, D. Genotype-phenotype relationships in studies of a polymorphism in NAD(P)H:quinone oxidoreductase 1. *Pharmacogenetics* (1999). , 9(1), 113-121.
- [68] Ross, D, & Siegel, D. NAD(P)H:quinone oxidoreductase 1 (NQO1, DT-diaphorase), functions and pharmacogenetics. *Methods in enzymology* (2004).
- [69] Eguchi-ishimae, M, Eguchi, M, Ishii, E, Knight, D, Sadakane, Y, Isoyama, K, Yabe, H, Mizutani, S, & Greaves, M. The association of a distinctive allele of NAD(P)H:quinone oxidoreductase with pediatric acute lymphoblastic leukemias with MLL fusion genes in Japan. *Haematologica* (2005). , 90(11), 1511-1515.
- [70] Krajcinovic, M, Sinnett, H, Richer, C, Labuda, D, & Sinnett, D. Role of NQO1, MPO and YP2E1 genetic polymorphisms in the susceptibility to childhood acute lymphoblastic leukemia. *International journal of cancer* (2002). , 97(2), 230-236.
- [71] Ross, J. A, & Kasum, C. M. Dietary flavonoids: bioavailability, metabolic effects, and safety. *Annual review of nutrition* (2002).
- [72] Hann, I. M, Stevens, R. F, Goldstone, A. H, Rees, J. K, Wheatley, K, Gray, R. G, & Burnett, A. K. Randomized comparison of DAT versus ADE as induction chemotherapy in children and younger adults with acute myeloid leukemia. Results of the Medical Research Council's 10th AML trial (MRC AML10). *Adult and Childhood Leukaemia Working Parties of the Medical Research Council. Blood* (1997). , 89(7), 2311-2318.
- [73] Leone, G, Fianchi, L, Pagano, L, & Voso, M. T. Incidence and susceptibility to therapy-related myeloid neoplasms. *Chemico-biological interactions* (2010).
- [74] Kyle, R. A, Pierre, R. V, & Bayrd, E. D. Multiple myeloma and acute myelomonocytic leukemia. *The New England journal of medicine* (1970). , 283(21), 1121-1125.

- [75] Kyle, R. A, Pierre, R. V, & Bayrd, E. D. Primary amyloidosis and acute leukemia associated with melphalan therapy. *Blood* (1974). , 44(3), 333-337.
- [76] Rosner, F, & Grünwald, H. Hodgkin's disease and acute leukemia. Report of eight cases and review of the literature. *The American journal of medicine* (1975). , 58(3), 339-353.
- [77] Reimer, R. R, Hoover, R, Fraumeni, JF Jr, & Young, RC. . Acute leukemia after alkylating-agent therapy of ovarian cancer. *The New England journal of medicine* (1977). , 297(4), 177-181.
- [78] Rowley, J. D, Golomb, H. M, & Vardiman, J. W. Nonrandom chromosome abnormalities in acute leukemia and dysmyelopoietic syndromes in patients with previously treated malignant disease. *Blood* (1981). , 58(4), 759-767.
- [79] Saffhill, R, Margison, G. P, & Connor, O. PJ. Mechanisms of carcinogenesis induced by alkylating agents. *Biochimica et biophysica acta* (1985). , 823(2), 111-145.
- [80] Horsfall, M. J, Gordon, A. J, Burns, P. A, Zielenska, M, Van Der Vliet, G. M, & Glickman, B. W. Mutational specificity of alkylating agents and the influence of DNA repair. *Environmental and molecular mutagenesis* (1990). , 15(2), 107-122.
- [81] Shulman, L. N. The biology of alkylating-agent cellular injury. *Hematology/oncology clinics of North America* (1993). , 7(2), 325-335.
- [82] Drabløs, F, Feyzi, E, Aas, P. A, Vaagbø, C. B, Kavli, B, Bratlie, M. S, Peña-diaz, J, Otterlei, M, Slupphaug, G, & Krokan, H. E. Alkylation damage in DNA and RNA-repair mechanisms and medical significance. *DNA Repair (Amst)* (2004). , 3(11), 1389-1407.
- [83] Pedersen-bjergaard, J, Pedersen, M, Roulston, D, & Philip, P. Different genetic pathways in leukemogenesis for patients presenting with therapy-related myelodysplasia and therapy-related acute myeloid leukemia. *Blood* (1995). , 86(9), 3542-3552.
- [84] Dissing, M, Le Beau, MM, & Pedersen-Bjergaard, J. . Inversion of chromosome 16 and uncommon rearrangements of the CBFβ and MYH11 genes in therapy-related acute myeloid leukemia: rare events related to DNA-topoisomerase II inhibitors? *Journal of clinical oncology* (1998). , 16(5), 1890-1896.
- [85] Smith, S. M, Le Beau, MM, Huo, D, Karrison, T, Sobecks, RM, Anastasi, J, Vardiman, JW, Rowley, JD, & Larson, RA. . Clinical-cytogenetic associations in 306 patients with therapy-related myelodysplasia and myeloid leukemia: the University of Chicago series. *Blood* (2003). , 102(1), 43-52.
- [86] Ross, J. A, Potter, J. D, & Robison, L. L. Infant leukemia, topoisomerase II inhibitors, and the MLL gene. *Journal of the National Cancer Institute* (1994). , 86(22), 1678-1680.
- [87] Nitiss, J. L. Targeting DNA topoisomerase II in cancer chemotherapy. *Nature reviews Cancer* (2009). , 9(5), 338-350.
- [88] Allan, J. M, & Travis, L. B. Mechanisms of therapy-related carcinogenesis. *Nature reviews Cancer* (2005). , 5(12), 943-955.

- [89] Joannides, M, & Grimwade, D. Molecular biology of therapy-related leukaemias. *Clinical & translational oncology* (2010). , 12(1), 8-14.
- [90] Salzer, W. L, Devidas, M, Carroll, W. L, Winick, N, Pullen, J, Hunger, S. P, & Camitta, B. A. Long-term results of the pediatric oncology group studies for childhood acute lymphoblastic leukemia 1984-2001: a report from the children's oncology group. *Leukemia* (2010). , 24(2), 355-370.
- [91] Pui, C. H, Ribeiro, R. C, Hancock, M. L, Rivera, G. K, Evans, W. E, Raimondi, S. C, Head, D. R, Behm, F. G, Mahmoud, M. H, Sandlund, J. T, et al. Acute myeloid leukemia in children treated with epipodophyllotoxins for acute lymphoblastic leukemia. *The New England journal of medicine* (1991). , 325(24), 1682-1687.
- [92] Neglia, J. P, Meadows, A. T, Robison, L. L, Kim, T. H, Newton, W. A, Ruymann, F. B, Sather, H. N, & Hammond, G. D. Second neoplasms after acute lymphoblastic leukemia in childhood. *The New England journal of medicine* (1991). , 325(19), 1330-1336.
- [93] Kreissman, S. G, Gelber, R. D, Cohen, H. J, Clavell, L. A, Leavitt, P, & Sallan, S. E. Incidence of secondary acute myelogenous leukemia after treatment of childhood acute lymphoblastic leukemia. *Cancer* (1992). , 70(8), 2208-2213.
- [94] Jankovic, M, Frascini, D, Amici, A, Aricò, M, Arrighini, A, Basso, G, & Colella, R. DiTullio MT, Haupt R, Macchia P, et al. Outcome after cessation of therapy in childhood acute lymphoblastic leukaemia. *The Associazione Italiana Ematologia ed Oncologia Pediatrica (AIEOP). European journal of cancer* (1993). A(13) 1839-1843.
- [95] Winick, N. J, Mckenna, R. W, Shuster, J. J, Schneider, N. R, Borowitz, M. J, Bowman, W. P, Jacaruso, D, Kamen, B. A, & Buchanan, G. R. Secondary acute myeloid leukemia in children with acute lymphoblastic leukemia treated with etoposide. *Journal of clinical oncology* (1993). , 11(2), 209-217.
- [96] Pagano, L, Annino, L, Ferrari, A, Camera, A, Martino, B, Montillo, M, Tosti, M. E, Mele, A, Pulsoni, A, Vegna, M. L, Leone, G, & Mandelli, F. Secondary haematological neoplasm after treatment of adult acute lymphoblastic leukemia: analysis of 1170 adult ALL patients enrolled in the GIMEMA trials. *Gruppo Italiano Malattie Ematologiche Maligne dell'Adulto. British journal of haematology* (1998). , 100(4), 669-676.
- [97] Armstrong, S. A, Golub, T. R, & Korsmeyer, S. J. MLL-rearranged leukemias: insights from gene expression profiling. *Seminars in hematology* (2003). , 40(4), 268-273.
- [98] Gewirtz, D. A. Does bulk damage to DNA explain the cytostatic and cytotoxic effects of topoisomerase II inhibitors? *Biochemical pharmacology* (1991). , 42(12), 2253-2258.
- [99] Vanhees, K, De Bock, L, Godschalk, R. W, & Van Schooten, F. J. van Waalwijk van Doorn-Khosrovani SB. Prenatal exposure to flavonoids: implication for cancer risk. *Toxicological sciences* (2011). , 120(1), 59-67.
- [100] Croft, K. D. The chemistry and biological effects of flavonoids and phenolic acids. *Annals of the New York Academy of Sciences* (1998).

- [101] Stalikas, C. D. Extraction, separation, and detection methods for phenolic acids and flavonoids. *Journal of separation science* (2007). , 30(18), 3268-3295.
- [102] Lanoue, L, Green, K. K, Kwik-uribe, C, & Keen, C. L. Dietary factors and the risk for acute infant leukemia: evaluating the effects of cocoa-derived flavanols on DNA topoisomerase activity. *Experimental biology and medicine* (2010). , 235(1), 77-89.
- [103] Balzer, J, Rassaf, T, Heiss, C, Kleinbongard, P, Lauer, T, Merx, M, Heussen, N, Gross, H. B, Keen, C. L, Schroeter, H, & Kelm, M. Sustained benefits in vascular function through flavanol-containing cocoa in medicated diabetic patients a double-masked, randomized, controlled trial. *Journal of the American College of Cardiology* (2008). , 51(22), 2141-2149.
- [104] Corder, R, Mullen, W, Khan, N. Q, Marks, S. C, Wood, E. G, Carrier, M. J, & Crozier, A. Oenology: red wine procyanidins and vascular health. *Nature* (2006).
- [105] Duthie, G, & Crozier, A. Plant-derived phenolic antioxidants. *Current opinion in clinical nutrition and metabolic care* (2000). , 3(6), 447-451.
- [106] Grassi, D, Aggio, A, Onori, L, Croce, G, Tiberti, S, Ferri, C, Ferri, L, & Desideri, G. Tea, flavonoids, and nitric oxide-mediated vascular reactivity. *The Journal of nutrition* (2008). S-1560S.
- [107] Adlercreutz, H, Markkanen, H, & Watanabe, S. Plasma concentrations of phyto-oestrogens in Japanese men. *Lancet* (1993). , 342(8881), 1209-1210.
- [108] Schröder-van der Elst JP van der Heide D, Rokos H, Morreale de Escobar G, Köhrle J. Synthetic flavonoids cross the placenta in the rat and are found in fetal brain. *The American journal of physiology* (1998). Pt 1) EE256., 253.
- [109] Strick, R, Strissel, P. L, Borgers, S, Smith, S. L, & Rowley, J. D. Dietary bioflavonoids induce cleavage in the MLL gene and may contribute to infant leukemia. *Proceedings of the National Academy of Sciences of the United States of America* (2000). , 97(9), 4790-4795.
- [110] Ross, J. A, Potter, J. D, Reaman, G. H, Pendergrass, T. W, & Robison, L. L. Maternal exposure to potential inhibitors of DNA topoisomerase II and infant leukemia (United States): a report from the Children's Cancer Group. *Cancer Causes Control* (1996). , 7(6), 581-590.
- [111] Jensen, C. D, Block, G, Buffler, P, Ma, X, Selvin, S, & Month, S. Maternal dietary risk factors in childhood acute lymphoblastic leukemia (United States). *Cancer Causes Control* (2004). , 15(6), 559-570.
- [112] Petridou, E, Ntouvelis, E, Dessypris, N, & Terzidis, A. Trichopoulos D; Childhood Hematology-Oncology Group. Maternal diet and acute lymphoblastic leukemia in young children. *Cancer epidemiology, biomarkers & prevention* (2005). , 14(8), 1935-1939.

- [113] Kwan, M. L, Jensen, C. D, Block, G, Hudes, M. L, Chu, L. W, & Buffler, P. A. Public health reports (2009). , 124(4), 503-514.
- [114] Sam, T. N, Kersey, J. H, Linabery, A. M, Johnson, K. J, Heerema, N. A, Hilden, J. M, Davies, S. M, Reaman, G. H, & Ross, J. A. MLL gene rearrangements in infant leukemia vary with age at diagnosis and selected demographic factors: a Children's Oncology Group (COG) study. Pediatric blood & cancer (2012). , 58(6), 836-839.