THE BIOLOGY OF PEDIATRIC ACUTE MEGAKARYOBLASTIC LEUKEMIA

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Abstract

Acute Megakaryoblastic Leukemia (AMKL) is a subtype of acute myeloid leukemia (AML) that morphologically resembles abnormal megakaryoblasts. While extremely rare in adults, pediatric cases comprise between 4 and 15% of newly diagnosed AML patients. AMKL in children with Down syndrome (DS) is characterized by a founding GATA1 mutation that cooperates with trisomy 21, followed by the acquisition of additional somatic mutations in epigenetic and kinase signaling genes. Clinically this manifests as a transient myeloproliferative disease (TMD) in the first year of life, followed by spontaneous resolution and the subsequent development into AMKL in a small fraction of patients with a latency of one to five years. Outcomes in DS-AMKL are excellent, with greater than 80% overall survival. In contrast, non-DS-AMKL is predominantly characterized by recurrent chimeric oncogenes comprised of genes known to play a role in normal hematopoiesis. These patients present acutely, ranging in age from infancy to adolescence. CBFA2T3-GLIS2 is the most frequent chimeric oncogene identified to date in this subset of patients, and carries an inferior event free and overall survival in contrast to non-DS-AMKL cases that lack this fusion protein. Thus efforts to target this oncogene will be important to improve outcomes.

Introduction

Acute Megakaryoblastic Leukemia (AMKL) is a subtype of acute myeloid leukemia (AML) characterized by abnormal megakaryoblasts that express platelet-specific surface glycoprotein. Bone marrow biopsy frequently demonstrates extensive myelofibrosis, often making aspiration in these patients difficult. AMKL is extremely rare in adults, occurring in only 1% of AML patients\(^1\). This is in contrast to children, where it comprises between 4 and 15% of AML patients\(^2,3\). In pediatrics, the disease is divided into two major subgroups: AMKL in patients with DS (DS-AMKL) and AMKL in patients without DS (non-DS-AMKL). AMKL is the most frequent type of AML in children with DS, and the incidence in these patients is 500-fold higher.
than in the general population\textsuperscript{4}. In contrast to non-DS-AMKL, leukemic cells not only carry megakaryocytic cell surface markers, but erythroid markers as well resulting in a distinct World Health Organization classification “myeloid leukemia in Down syndrome”\textsuperscript{5}. Somatic mutations in $GATA1$ are found in almost all cases of DS-AMKL and precede the development of leukemia as indicated by their presence in patients with transient myeloproliferative disease (TMD) in the neonatal period\textsuperscript{6-11}. DS-AMKL is not only biologically distinct, but clinically distinct as well, with superior outcomes compared to non-DS-AMKL\textsuperscript{12-15}. Pediatric non-DS-AMKL is a heterogenous group of patients, a significant proportion of which carry chimeric oncogenes including $RBM15-MKL1$, $CBFA2T3-GLIS2$, $NUP98-KDM5A$, and $MLL$ gene rearrangements\textsuperscript{16,17}. Unfortunately, the outcome of non-DS-AMKL is generally poor, with lower event free survival than DS-AMKL and pediatric AML, even in the face of intensified treatment\textsuperscript{2,18}.

\textbf{DS-AMKL}

\textbf{Transient Myeloproliferative Disease}

DS-AMKL is associated with a hematologic disorder in infancy, termed transient myeloproliferative disease (TMD). In this disorder, a clonal population of megakaryoblasts accumulate in the peripheral blood. These blasts are phenotypically indistinguishable from AMKL leukemic blasts and in the majority of cases, remission is spontaneous within 3 months in the absence of treatment. In approximately 20% of TMD cases, patients will go on to develop MDS and/or AMKL\textsuperscript{19}. TMD is felt to originate \textit{in utero}, as an identical mutation in $GATA1$, the genetic lesion associated with TMD, was found to be present at birth in twins that suffered from TMD\textsuperscript{20}. Further evidence came with the analysis of archived autopsy specimens from DS patients that identified $GATA1$ mutations in two fetal liver specimens\textsuperscript{21}. A subsequent study screening Guthrie cards from 585 DS infants identified $GATA1$ mutations in 3.8\% of their cohort, confirming the presence of this lesion in a subset of patients at birth\textsuperscript{22}. The frequency of this lesion in newborn DS patients was found to be significantly higher in a study that utilized next
generation sequencing, which carries a greater sensitivity, to screen 200 neonates with DS\textsuperscript{23}. In this analysis \textit{GATA1} mutations were detected in 29\% of patients. The spontaneous resolution of TMD suggests that despite the presence of blasts in the peripheral blood that appear phenotypically indistinguishable from full blown leukemia, they are in fact functionally different as they fail to persist. When TMD and AMKL blasts from patients with DS are injected into immunodeficient mice, this difference becomes apparent. Approximately 50\% of DS-AMKL engraft into NOD/SCID mice leading to widespread dissemination and the ability to propagate in secondary and tertiary recipients\textsuperscript{24}. In contrast, blasts from TMD patients very rarely engraft, fail to disseminate outside the bone marrow, and are unable to propagate disease in secondary and tertiary recipients\textsuperscript{24}. Exome sequencing of TMD has revealed that non-silent mutations in these blasts are primarily limited to the \textit{GATA1} gene\textsuperscript{25}. In contrast, AMKL blasts carry a higher burden of mutations, with additional lesions in epigenetic and kinase signaling genes leading to progression of the disease. Collectively, these findings support a model whereby TMD blasts arise secondary to \textit{GATA1} mutations in the setting of trisomy 21, acquiring this so-called “first hit” and persist in the bone marrow. Additional lesions can then occur providing the cooperating events that are necessary for full blown leukemia to develop (Figure 1). While sequencing studies have demonstrated the genetic lesions that are required for progression of TMD to AMKL, they do not provide any information on how to predict the 20\% of patients that will go on to develop AMKL. An extensive analysis of germline DNA including pathologic mutations in cancer predisposition genes as well as GWAS studies to identify polymorphisms that may predispose an individual to developing AMKL may provide clues. If predisposing factor(s) are identified, they have the potential to significantly impact clinical care, as the identification of those patients with a high risk of developing AMKL would allow for early treatment of the premalignant cells with decreased intensity chemotherapy while maintaining the high cure rates.
The GATA family of proteins are transcription factors, three of which are expressed principally in hematopoietic cells (GATA1, GATA2, and GATA3). The GATA1 protein is typically present in cells of erythroid, megakaryocytic, mast and eosinophilic lineages while GATA2 is expressed in early hematopoietic progenitors. GATA1 is required for the development of erythrocytes, megakaryocytes, eosinophils, and mast cells. Mutations in GATA1 have been associated with thrombocytopenia, Familial Dyserythropoietic anemia, thalassemia, porphyria, Diamond-Blackfan anemia, TMD, and DS-AMKL. The mutations found in non-malignant diseases either weaken or eliminate the interaction of GATA1 with its cofactor FOG1, or interfere with DNA binding. In contrast, the mutations detected in DS patients consist of short deletions, insertions, and point mutations within exon 2 that introduce a premature stop codon. This shorter mutant protein retains the ability to bind DNA and interact with its cofactor, but lacks the transcriptional activation domain and hence has reduced transactivation potential. To model TMD, a knock-in line of mice expressing a truncated form of GATA1 was generated and found to result in hyperproliferative megakaryocytic progenitors in the yolk sac and fetal liver that disappeared by the end of gestation. A separate group crossed mice transgenic for a truncated form of GATA1 to the GATA1 knockout strain. During the neonatal period, mice accumulate immature megakaryocytic progenitors in the liver that disappear during weaning of the pups. Regardless of the difference in timing, these models serve to validate that a truncated GATA1 protein is able to confer a proliferative advantage, generating a pool of precursors that have the potential to develop into a leukemic population. The mechanism whereby truncated GATA1 is able to induce a preleukemic state is not fully elucidated, although genome-wide chromatin immunoprecipitation sequencing (ChIP-seq) of genes bound by GATA1 merged with expression profiling revealed a large number of activated and repressed genes respectively that were occupied by the GATA1 protein. Further studies have shown that GATA1 is able to activate lineage specific genes and repress progenitor maintenance genes depending on the
cofactors present. It is therefore plausible, that deregulation of these targets contributes to the
differentiation arrest seen with the truncated GATA1 that is no longer able to transactivate
transcription of lineage specific genes. A second mechanism proposed is the upregulation of
genes by mutant GATA1 that promote self-renewal, as has been demonstrated for the
microRNA miR-486-5p. Additionally, it is possible that the extra gene dosage of chromosome
21 contributes to this process; in fact trisomy 21 has an impact on fetal hematopoiesis in and of
itself. Fetal livers from DS patients have a 2-3 fold increase in megakaryocyte erythroid
progenitors, and trisomic stem cells exhibit alterations of hematopoiesis in vitro with an increase
in multilineage colony-forming potential, an indicator of increased self-renewal. Supporting
this cooperativity between GATA1 mutations and trisomy 21 is the specificity of GATA1
mutations: almost without exception, GATA1 mutations are not found outside the context of
trisomy 21. Even in rare cases of non-DS-AMKL that carry GATA1 mutations, somatic copy
number amplifications in the DS critical region of chromosome 21 are found to be present.

Patients with trisomy 21 have, in essence, an extra copy of many genes on chromosome 21
(chr21) and overexpression of one or more have been hypothesized to provide the cellular
setting that is permissible for persistence and eventual transformation of GATA1 mutant cells.
Candidate genes on chr21 that contribute to a preleukemic phenotype include but are not
limited to ERG, RUNX1, DYRK1A, and MIR125B2. ERG, is a member of the ETS
transcription gene family. Increased expression of ERG is seen in some cases of AML and it is
also a translocation partner in t(16;21) myeloid leukemia. ERG has been recently shown to
play a role in hematopoietic stem cells as well as the development of the megakaryocytic
lineage, and furthermore transgenic expression of ERG and a mutant GATA1 protein in murine
fetal liver cells results in a TMD like disease. Additionally, over-expression of ERG in
hematopoietic progenitor cells by retroviral transduction and subsequent transplantation into
mice results in megakaryoblastic leukemia. Another candidate is the RUNX1 gene, also found
on chr21. Perhaps counterintuitively, RUNX1 expression was found to be lower in DS-AMKL cases in comparison to non-DS-AMKL in two separate cohorts despite the increase number of genomic copies. While the mechanism of this downregulation is not clear, in core binding factor leukemias a decrease in RUNX1 activity either by mutation or the transdominant effect of a translocation involving RUNX1 is associated with increased leukemic potential. Thus a downregulation of RUNX1 in DS-AMKL would be consistent with previous data that a loss of RUNX1 wild type function enhances self-renewal and blocks differentiation. In line with this hypothesis, RUNX1 up-regulation was found to precede megakaryocyte differentiation in human hematopoietic cells and down-regulation was seen when cells underwent erythroid differentiation suggesting that it functions in megakaryocytic lineage commitment. A decrease in RUNX1 could therefore impair differentiation allowing persistence of GATA1 mutant cells in a more immature state.

Cooperating Mutations

Given that only 20% of TMD progresses to leukemia, what then are the subsequent events or alterations that promote the preleukemic state to that of a fully transformed malignancy? Exome and targeted sequencing of 46 genes has provided insight to this question, identifying recurrently mutated genes in three major categories: cohesin, epigenetic regulators, and signaling molecules. Core cohesin complex components including STAG2, RAD21, SMC3, SMC1A, and the cohesin complex loading protein NIPBL were mutated in 53% of the 49 DS-AMKL cases and none of the 41 TMD cases interrogated. This is a significantly higher than the reported frequency of 6-12% in AML, suggesting these mutations may play a specific role in promoting megakaryocytic disease. Additionally, 6 cases carried mutations in CTCF, a transcriptional repressor and insulator protein. Cohesin maintains sister chromatid cohesion, allowing for faithful chromosome segregation and DNA repair. In addition, the complex also functions in transcriptional regulation through DNA looping. CTCF and cohesin have been
found to co-localize extensively throughout mammalian genomes\textsuperscript{57}. It has been suggested that together, they play a role in the establishment and maintenance of topological domains\textsuperscript{58}. Their disruption thus has the potential to significantly disrupt chromatin architecture and in doing so, gene expression. Interestingly, GATA1 has been found to co-occupy genes with the RAD21 cohesin component as well as CTCF in adult pro-erythrocytes (796 and 656 target genes respectively) providing direct evidence for cooperative effects between these genes\textsuperscript{59}.

EZH2, the catalytic subunit of the Polycomb repressive complex 2 (PRC2) was the most frequently targeted epigenetic regulator in DS-AMKL. Combined with SUZ12, PRC2 mutations were mutually exclusive and collectively occurred in 17 of 49 cases (35%), the majority of which also contained alterations in CTCF or cohesin. In erythroid cells, PRC2 is involved in epigenetic silencing of a subset of GATA1-repressed genes, some of which are associated with progenitor cells such as KIT and GATA2\textsuperscript{60}. Disruption of the repression may therefore enhance the self-renewal of cells, contributing to the differentiation block provided by the truncated GATA1 protein.

Close to 50\% of DS-AMKL cases carry activating kinase mutations in JAK1, JAK2, JAK3, MPL, KRAS, NRAS, or loss of function mutations in SH2B3. These kinase genes fall broadly into two categories: JAK/STAT and RAS signaling, both of which play a role in megakaryopoiesis (Figure 2)\textsuperscript{61,62}. Mutations between these two signaling cascades are for the most part, mutually exclusive, although occasional cases carry a lesion in both. They result in constitutively activated signaling, leading to a gain of function as demonstrated by cytokine-independent growth in laboratory assays\textsuperscript{63-65}. Over-expression of one of the DS-AMKL associated JAK3 activating mutations has been shown to result in a lethal megakaryocyte progenitor expansion in a subset of mice, further supporting this signaling pathway in AMKL\textsuperscript{64}. 
Non-DS-AMKL

RBM15-MKL1

The t(1;22) translocation and its association with AMKL in infants was initially identified in a cohort of 252 children with AML accrued over a 24 month period\textsuperscript{66}. In this report, no cases of t(1;22) were identified in a concurrent pediatric ALL cohort of 2382 cases and the translocation was exclusively found in patients with AMKL, all of which were less than 1 year of age. This fusion was very specific for infant AMKL as the 22 other infants with AML that lacked the translocation had a different phenotypic subtype. Further, the remaining 12 non-DS-AMKL cases carried no recurring chromosomal abnormalities and were all older in age. Others have since confirmed this association, but it wasn’t until 10 years after the initial report that the genes involved in the translocation were characterized\textsuperscript{67-70}. Two groups simultaneously identified the genes on chromosomes 1 and 22 involved in the translocation, \textit{RBM15} (also known as \textit{OTT}) and \textit{MKL1} (also known as \textit{MAL}) respectively\textsuperscript{67,70}. Since their initial cloning, much has been learned about the function of the genes and a role of the translocation in inducing leukemia has been demonstrated in a knock-in mouse model\textsuperscript{71}.

\textit{MKL1} is a transcriptional coactivator for serum response factor (SRF), a transcription factor that regulates the expression of genes involved in cell growth, proliferation, differentiation, and genes that control the actin cytoskeleton\textsuperscript{72}. In serum starved cells MKL1 associates with G actin monomers and is retained in the cytoplasm. Following serum stimulation and Rho-mediated actin polymerization, G actin pools are depleted and MKL1 translocates to the nucleus, associating with SRF to activate gene transcription\textsuperscript{73,74}. During murine megakaryocyte differentiation, \textit{Mkl1} is upregulated. Consistent with this, \textit{Mkl1} knockout mice have an increased percentage of megakaryocytic progenitors, a decrease in mature megakaryocytes, as well as dysplastic megakaryocytes\textsuperscript{75,76}. RBM15 belongs to the Spen family of proteins and encodes a protein containing three amino-terminal RNA recognition motifs that bind to nucleic acids and a
C-terminal SPOC domain that is thought to interact with the SMRT and NCoR corepressor complexes as well as RBPJ, a transcription factor downstream of Notch signaling\textsuperscript{77,78}. \textit{Rbm15} knockout mice are embryonic lethal, thus to evaluate the effect of this protein on hematopoiesis, conditional knockout mice have been generated\textsuperscript{79,80}. These mice have a block in B lymphopoiesis and expansion of the myeloid, megakaryocytic, and progenitor compartments\textsuperscript{75,79}. The fusion of MKL1 to RBM15 deregulates the normal intracellular localization of MKL1 such that it becomes constitutively localized to the nucleus resulting in SRF activation even in the absence of stimuli\textsuperscript{81}. In addition to the SRF transcriptional program, the fusion also aberrantly activates RBPJ transcriptional targets. While both transcription programs have been shown to be deregulated by the fusion gene, the degree to which they contribute to transformation is still unclear.

In studies done to address the role of the \textit{RBM15-MKL1} chimeric gene in AMKL, knock-in mice were engineered to express the chimeric oncogene under control of the endogenous \textit{Rbm15} promoter\textsuperscript{71}. These mice display abnormal fetal and adult hematopoiesis with a small fraction developing AMKL between 18-24 months of age\textsuperscript{71}. Using this mouse model, the authors present data to support \textit{RBM15-MKL1} activated RBPJ mediated transcriptional activity that leads to upregulation of the Notch pathway\textsuperscript{71}. Consistent with this, Rbm15 has been shown to modulate Notch induced transcription in a cell type specific manner\textsuperscript{82}. Given that only a fraction of mice developed overt AMKL at a late age, the authors reasoned that cooperating oncogenic events were required to induce AMKL. The identification of such cooperating mutations has proved elusive due to a paucity of clinical samples with high tumor content for next generation sequencing analysis. Nonetheless, careful analysis of one patient specimen along with a matched germline specimen revealed 12 high confidence mutations, one of which occurred in \textit{MMP8}, a matrix metalloproteinase gene that is expressed in megakaryocyte-erythroid
progenitors\textsuperscript{83}. Further studies are necessary to determine if this mutation is able to cooperate with the \textit{RBM15-MKL1} oncogene.

\textbf{CBFA2T3-GLIS2}

Until recently, with the exception of the \textit{RBM15-MKL1} fusion, the genetic etiology of non-DS-AMKL had remained elusive. A high resolution study of DNA copy number abnormalities (CNAs) and loss of heterozygosity on pediatric \textit{de novo} AML samples demonstrated a very low burden of genomic alterations in all pediatric AML subtypes with the exception of AMKL\textsuperscript{84}. AMKL cases were characterized by complex chromosomal rearrangements and a high number of CNAs. We predicted that these lesions would have functional consequences and therefore, performed transcriptome and exome sequencing on diagnostic leukemia samples from 14 pediatric non-DS-AMKL cases as part of the St. Jude Children’s Research Hospital – Washington University Pediatric Cancer Genome Project\textsuperscript{16}. Indeed, we detected structural variations (SVs) that resulted in the expression of chimeric transcripts in 12 of 14 samples. Remarkably, in 7 of 14 cases a cryptic inversion on chromosome 16 [inv(16)(p13.3q24.3)] was detected that resulted in the joining of \textit{CBFA2T3}, a member of the ETO family of nuclear corepressors, to \textit{GLIS2}, a member of the GLI family of transcription factors\textsuperscript{16}. The gene expression profile of \textit{CBFA2T3-GLIS2} AMKL was distinct from that of AMKL cells lacking this chimeric transcript, and from other genetic subtypes of pediatric AML\textsuperscript{16}. Furthermore, the \textit{CBFA2T3-GLIS2} fusion gene conferred a poor prognosis, a finding which has since been confirmed\textsuperscript{16,17,85}. This fusion was subsequently reported to also occur at a low frequency in pediatric cytogenetically normal AML\textsuperscript{85}. Expression of \textit{CBFA2T3-GLIS2} in \textit{Drosophila} and murine hematopoietic cells induced bone morphogenic protein (BMP) signaling, a pathway not previously implicated in AML, and resulted in a marked increase in the self-renewal capacity of hematopoietic progenitors\textsuperscript{16}. The contribution of BMP signaling to self-renewal in \textit{CBFA2T3-
GLIS2 modified murine hematopoietic cells has since been confirmed in colony formation assays utilizing Bmp2 and Bmp4 conditional knockout marrow (unpublished data).

CBFA2T3-GLIS2 expressing cells remained growth factor dependent in vitro suggesting that cooperating mutations in growth factor signaling pathways are likely required for full leukemic transformation. Moreover, transplantation of CBFA2T3-GLIS2 transduced bone marrow cells into syngeneic recipients failed to induce overt leukemia, consistent with a requirement for cooperative mutations. Failure to induce leukemia in mice as a single lesion has been previously reported for other chimeric genes that confer the ability to serially replate in colony forming assays, including AML1-ETO. Overall, the total burden of somatic mutations in our cohort was significantly lower in the CBFA2T3-GLIS2 expressing cases for which germline DNA was available compared to non-DS-AMKL that lacked this fusion gene (7.2 ± 3.6 versus 16.6 ± 5.1, p=0.009). Of the fifteen CBFA2T3-GLIS2 positive cases analyzed to date, five carried lesions in either a Janus Kinase (JAK) gene and/or a somatic amplification of the DS critical region on chromosome 21. However, the majority of cases do not contain an identifiable cooperating lesion (unpublished data and). As these cases have been interrogated by single nucleotide polymorphism arrays, exome, and/or transcriptome sequencing, a more thorough whole genome approach may help to further delineate the additional events required by this fusion oncogene. Whole genome sequencing would allow the identification of somatic mutations in noncoding intergenic regions that are oncogenic. Examples of these types of lesions include TERT promoter mutations and super-enhancer formation upstream of the TAL1 oncogene, as identified in melanoma and T cell acute lymphoblastic leukemia respectively.

Lower Frequency Fusion Events

In addition to CBFA2T3-GLIS2, we identified approximately 8% of our pediatric cohort to carry the previously described NUP98-KDM5A fusion gene (Figure 3). In parallel with our efforts, de
Rooij and colleagues evaluated a separate non-DS-AMKL cohort for \textit{NUP98} fusion events by split-signal fluorescence in situ hybridization and found a similar frequency of 11\%\textsuperscript{17}. \textit{NUP98}, a nucleoporin family member with transactivation activity, fused to \textit{KDM5A}, an H3K4me3 binding PHD finger, was initially described in adult AML\textsuperscript{89,90}. When introduced into murine bone marrow this fusion oncogene induces a myeloid differentiation arrest and mice develop AML with an average latency of 69 days\textsuperscript{91}. Wang and colleagues demonstrated this fusion to be bound to H3K4me3 mononucleosomes, showing the PHD finger plays a role in targeting the fusion to the genome\textsuperscript{91}. Interestingly, microarray analysis identified several polycomb proteins carrying H3K4me3 marks to be transcriptionally upregulated in response to the fusion, while housekeeping genes with constitutive H3K4me3 marks remained unchanged. Affected polycomb targets confirmed by chromatin immunoprecipitation include genes upregulated in \textit{MLL} rearranged leukemia such as \textit{HOXA5, HOXA7, HOXA9, HOXA10, MEIS1}, and \textit{PBX1}\textsuperscript{91}. Furthermore, the authors demonstrate a block in PRC2 binding, the complex that antagonize polycomb proteins through transcriptional repression of target genes. Therefore, the \textit{NUP98-KDM5A} fusion is able to prevent silencing of critical transcription factors that play a role in maintaining hematopoietic progenitor status, similar to \textit{MLL} gene rearrangements. It is perhaps not surprising then, that \textit{MLL-AF9} and \textit{MLL-AF10} fusion events have also been detected in non-DS-AMKL\textsuperscript{17}. As these lesions are also found in other subtypes of AML, there are likely additional factors contributing to the development of megakaryoblastic disease. Cooperating mutations, the target cell, and the microenvironment all have the potential to direct lineage during the process of transformation.

In addition to the previously described \textit{NUP98-KDM5A} fusion we identified three novel fusion genes expressed in a single case each: \textit{GATA2-HOXA9, MN1-FLI1}, and \textit{NIPBL-HOXB9} (Figure 3). Each of these chimeric transcripts are predicted to encode a fusion protein that would alter signaling pathways known to play a role in normal hematopoiesis suggesting that
these lesions are “driver” mutations that directly contribute to the development of leukemia. Several of the genes involved in these translocations play a direct role in normal megakaryocytic differentiation (GATA2 and FLI1), have been previously shown to be involved in leukemogenesis (HOXA9, MN1, HOXB9), or are highly expressed in hematopoietic stem cells or myeloid/megakaryocytic progenitors. Genome wide approaches in a larger AMKL cohort are necessary to determine if these fusion genes are recurrent. Current efforts in our laboratories include experiments to determine the ability of these fusion genes to enhance self-renewal, block differentiation, and induce leukemia in murine model(s) with a focus on the mechanism whereby these processes take place.

**Conclusion**

Pediatric AMKL is a heterogeneous disease comprised on chimeric oncogenes or truncating GATA1 mutations that enhance self-renewal and block myeloid differentiation. Cooperating mutations that contribute to transformation include amplifications of chromosome 21 (either somatic or constitutional) as well as SNVs/Indels in cohesin complex genes, CTCF, epigenetic regulators, and kinases genes. In approximately 35% of pediatric non-DS-AMKL cases the genetic alterations leading to the malignancy are unknown warranting further comprehensive genomic studies (Figure 3). CBFA2T3-GLIS2 is the most frequent fusion event with a distinct biology in addition to a poor prognosis, occurring in 18% of patients. Development of targeted agents that inhibit the fusion directly, or critical self-renewal pathways upregulated as a result of the fusion, such as BMP, may provide therapeutic benefit. The diversity of CBFA2T3-GLIS2 negative non-DS-AMKL cases suggest that alternative less targeted approaches, such as the promotion of megakaryoblast differentiation, should be evaluated in an attempt to improve outcomes across patients with a wide spectrum of mutations. The presence of JAK/STAT and RAS pathway activating mutations provides a rationale for the use of kinase inhibitors,
although their role as cooperating hits warrants caution as these agents may be additive to existing treatment but not sufficient to eliminate disease on their own.

Authorship

Contribution: T.A.G. and J.R.D. wrote the manuscript.

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References


Figure Legends

Figure 1. DS-AMKL Pathogenesis. In utero truncating mutations in GATA1 lead to a transient myeloproliferative disease (TMD) in the neonatal period that resolves in the absence of treatment. Residual cells either undergo apoptosis, or acquire additional cooperating mutations leading to overt AMKL with an average latency of 3 years. Recurrently targeted genes include but are not limited to cohesin complex components, CTCF, the PRC2 complex, and kinase signaling genes. Of the 26 sequenced DS-AMKL cases that carry mutations in cohesin, six contained mutations in a PRC2 complex gene as well as a kinase as shown in this example. Trisomy 21 = x × x ×, GATA1 mutation = ●, Cohesin mutation = ●, PRC2 mutation = ■, Kinase mutation = ▲.

Figure 2. JAK Signaling in Megakaryopoiesis. Cytokine binding to its cellular receptor leads to dimerization and phosphorylation that in turn binds and activates JAK leading to downstream activation of RAS signaling and phosphorylation of STAT transcription factors. SHC1 = adapter molecule, SH2B3 = inhibitor of JAK2. Receptors and kinases with activating mutations identified in AMKL include MPL, PDGFRB, JAK1, JAK2, JAK3, NRAS, and KRAS. Mutations in SH2B3 have been identified in DS-AMKL.

Figure 3. Key Genomic Events in Non-DS-AMKL. 142 pediatric non-DS-AMKL cases were analyzed for the presence of fusion gene events by transcriptome sequencing, RT-PCR, or split-signal fluorescence in situ hybridization. 96 samples were evaluated for the presence of the MLL-PTD by RT-PCR and 46 samples were evaluated for the presence of somatic GATA1 single nucleotide variations (SNVs) and insertion/deletion (Indels) by exome and/or sanger sequencing. Proportion of MLL-PTD and GATA1 mutant cases were calculated based on the total number of samples evaluated for each of the lesions. Patients carrying GATA1 mutations did not have stigmata of DS nor evidence of mutant reads in germline DNA suggesting they are not mosaics. Cases that did not undergo transcriptome sequencing and were negative by RT-PCR for CBFA2T3-GLIS2, NUP98-KDM5A, RBM15-MKL1, and MLL rearrangements (MLLr) are designated as unknown. “Other fusion” include single cases of each of the following: GATA2-HOXA9, NIPBL-HOXB9, MN1-FLI1, HLXB9-ETV6, FUS-ERG, and RUNX1-CBFA2T3. Data compiled from16,17.
Figure 3

- **Unknown**: 35%
- **CBFA2T3-GLIS2**: 17%
- **NUP98-KDM5A**: 11%
- **RBM15-MKL1**: 13%
- **MLLr**: 10%
- **GATA1**: 7%
- **Other Fusion**: 5%
- **MLL PTD**: 3%
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