Megakaryocyte Pathology and Bone Marrow Fibrosis: the Lysyl Oxidase Connection

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Abstract

Megakaryocytes (MKs), the platelet precursors, are capable of accumulating DNA greater than a diploid content as part of their cell cycle. MKs have been recognized as mediating fibrosis in a subset of hematological malignancies, including Acute Megakaryoblastic Leukemia and a subset of Myeloproliferative Neoplasms. The mechanisms responsible for fibrosis remain only partially understood. Past studies highlighted the role of growth factors in such pathologies, and recently, the protein lysyl oxidase (LOX) has been implicated in proliferation of MKs, ploidy and deposition of fibers. LOX was initially characterized as a protein responsible for the intermolecular cross-linking of elastin and collagen, and in recent years it has been identified as regulator of various pathologies, such as cancer and inflammation. Here, we review recent advances in the understanding of the contribution of MKs to the progression of myelofibrosis, highlighting the newly identified role of LOX.
The Megakaryocyte and Leukemia

Megakaryocytes (MKs) share a common progenitor with red blood cells, and are responsible for the production of platelets. MKs are unique among blood cells in their ability to attain states of high ploidy (up to 256 N) by endomitosis, a process that involves multiple cycles of aborted late anaphase and cytokinesis and re-entrance into G1 phase of the cell cycle. Thrombopoietin, or TPO, is the ligand for the MPL receptor and the key growth factor of megakaryopoiesis. TPO interaction with its receptor activates several signaling pathways, including RAS/MAPK and JAK-STAT which lead to MK endomitosis and maturation. The JAK2 protein is instrumental in relaying signaling from the TPO receptor to downstream pathways.

Proliferation of MKs is tightly controlled and the rare Acute Megakaryoblastic Leukemia (AMKL) is characterized by blasts often resembling lymphoid cells with a variable staining pattern. In children, two distinct AMKL types can be recognized, depending on whether AMKL occurs in the context of Down Syndrome (DS) or not. Pediatric non-DS-AMKL is a heterogeneous disorder and includes cases with t(1;22)(p13;q13) chromosomal translocation that primarily occurs in infants. This translocation leads to the formation of the chimeric protein OTT-MAL composed of RNA binding motif protein 15 (RMBM15, aka OTT) and the megakaryoblastic leukemia 1 gene (MKL1, aka MAL). In contrast, virtually all cases of DS-AMKL mutations affect the GATA-1 gene, although other, not well-defined, cooperative lesions are also required for the development of DS-AMKL. The transcription factor GATA-1 plays a key role in megakaryopoiesis and erythropoiesis and has a complex expression pattern (reviewed in ). The reported mutations of GATA-1 in DS-AMKL result in a smaller GATA-1 protein (GATA-1s), with reduced transactivation ability due to loss of the amino terminal activation domain. Children suffering from DS are not susceptible to the development of solid tumors, but are uniquely predisposed to develop AMKL. In addition, approximately 10% of children suffering from DS develop Transient Myeloproliferative Disease (TMD). This is usually a self-limited condition marked by hyper-proliferation of megakaryoblasts in blood and liver, but in 20% of cases it may progress to AMKL. Importantly, mutations in GATA-1 have also been reported in non-DS-AMKL, but only in very rare cases. In adult AMKL the molecular lesions are more diverse and include chromosomal deletions and translocations. Mutations affecting the JAK3 protein have been found in a small subset of patients suffering from AMKL regardless of DS context; none of the patients harbored mutations of JAK2 protein.
An intriguing entity is the exceedingly rare familial infantile myelofibrosis (FIM) disorder characterized by myelofibrosis, splenomegaly and extramedullary hematopoiesis. The pathophysiology of FIM remains largely unexplored.

The Megakaryocyte and Myeloproliferative Neoplasms

The term “myeloproliferative disorders” was introduced in 1951. Today, the scope of myeloproliferative disorders has been expanded, and reclassified under the nomenclature of myeloproliferative neoplasms (MPN). According to the World Health Organization (WHO) 2008 classification, MPNs encompass Chronic Myeloid Leukemia (CML), Polycythemia Vera (PV), Essential Thrombocythemia (ET), Primary Myelofibrosis (PMF), Mast Cell disease, Chronic Eosinophilic Leukemia (not otherwise categorized), Chronic Neutrophilic Leukemia and others unclassifiable (Discussed in ). MKs are involved in the pathologies of ET, PV and PMF, which share a common molecular defect: namely, a somatic mutation affecting JAK2, the JAK2V617F, which is detected in the overwhelming majority of PV patients and occurs also in approximately 60% of ET and PMF patients. The JAK2V617F mutation affects the pseudokinase domain of JAK2 and renders this kinase constitutively active, independently of ligand binding (reviewed in ).

Other less common molecular lesions involve JAK2 exon 12 and the MPLW515L/K mutations. Interestingly, the transcription factor NF-E2, which has a key role on the megakaryocytic lineage, was recently found overexpressed in patients suffering from MPNs, independent of the presence of the JAK2V617F mutation. Intriguingly, a mutation affecting JAK2T875N (identified in a cell line originating from an infant with AMKL accompanying myelofibrosis) was shown in BM transplantation assay to exhibit characteristics of both AMKL and MPN.

It remains unclear how a single mutation can result in different MPNs, although methylation of microRNA, allele burden and other synergistic mutations may be involved. PV and ET have insidious presentation and are usually chronic, indolent conditions but may progress to post-PV or post-ET myelofibrosis, respectively, or to secondary leukemia. Patients suffering from ET have very high levels of platelets with a fairly normal hematocrit, and increased risk of thrombosis and, paradoxically, of bleeding too. In ET bone marrow (BM) biopsies, MKs, although numerous, appear large and mature. By contrast, in PV both the hematocrit and platelet levels are significantly elevated, and BM biopsies reveal hyperplasia of all blood cell lineages.
Diagnosis post-PV or post-ET myelofibrosis can be challenging, and criteria were proposed by the International Working Group for Myelofibrosis Research and Treatment (IWG-MRT)\textsuperscript{22} to aid in its diagnosis. According to one study, 6\% of patients affected by PV are at risk of progression to post-PV myelofibrosis within 15 years\textsuperscript{23}. The development of post-PV myelofibrosis is an ominous sign and patients succumb within a few years\textsuperscript{24, 25}. Although ET is accompanied by some degree of reticulin fibrosis, few ET patients will develop myelofibrosis within 15 years. Of note, in a study the degree of reticulin fibrosis in ET patients was associated with higher complication rates\textsuperscript{26}. In addition, reticulin content was an independent risk factor for progression to transformation\textsuperscript{27}.

By contrast, PMF (also known as idiopathic myelofibrosis or myelofibrosis with myeloid metaplasia) has an aggressive course with median survival of 5 years\textsuperscript{28}. Patients suffer from anemia, extramedullary hematopoiesis, splenomegaly and typically intense BM fibrosis with early mobilization of hematopoietic stem cells (HSC)\textsuperscript{29}. Peripheral blood smear reveals giant degranulated platelets and dacryocytes, and the BM is infiltrated by numerous abnormal MKs with misfolded nuclei.

Several scoring systems have been proposed in an attempt to determine prognosis in patients affected by PMF. These include the International Prognostic Scoring System (IPSS), Dynamic IPSS (DIPSS) and DIPSS plus (discussed in \textsuperscript{30}). Common variables include age, anemia, leukocytosis, and presence of blasts or constitutional symptoms, while DIPPS plus includes also thrombocytopenia, certain karyotypes and need for blood transfusions. Although the degree of fibrosis is not used in these scores the grade of BM fibrosis is associated with overall survival at least in intermediate and high risk patients\textsuperscript{31}. Treatment options for PMF are limited despite several clinical trials\textsuperscript{32}. Allogenic HSC transplant is currently the most promising therapy\textsuperscript{28}.

**BM Fibrosis in the Context of MK Pathology**

The term myelofibrosis is loosely used in the literature and may indicate BM deposition of reticulin, collagen, or both, regardless of the nosogenic background; severity can range from scattered to a heavily fibrotic marrow\textsuperscript{33}. Reticulin can be detected with silver-based stains (e.g. Gomori stain) and collagen with trichrome stains (e.g. Mallory’s or Masson’s Trichrome stain). Grading schemes have been developed for reticulin deposition, and the most frequently used one is the Bauermeister scale\textsuperscript{34}. Few studies have evaluated reticulosis in healthy individuals\textsuperscript{33}. Some degree of reticulosis was detected in a significant number of healthy individuals\textsuperscript{34}. However, in a
study involving 100 non-hematological patients, neither Grade 3 nor Grade 4 reticulosis on the Bauermeister scale (diffuse fiber deposition and areas of collagen deposition respectively) was observed. Reticulin deposition is not currently used to determine prognosis in the context of MPN. On the other hand, collagen deposition is generally regarded as a more ominous finding. Ideally, both reticulin and collagen deposition should be evaluated; however, this is rarely done, and usually only reticulin is assessed in murine model studies.

In the context of AMKL and certain myeloproliferative disorders, BM fibrosis usually involves deposition of both reticulin and collagen fibers. A significant proportion of AMKL cases develop myelofibrosis that may be so extensive as to prevent BM aspiration. A study demonstrated that supernatant from AMKL megakaryoblasts and the megakaryoblastic cell line MEG-01 potently induced collagen production in fibroblasts, and that TGF-β was a key mediator of this effect. In another report, a patient with chronic myelofibrosis progressed to transformation into acute micromegakaryocytic leukemia (blast ploidy ≥ 4N). Importantly, the levels of TGF-β and PDGF as well as the markers of collagen I and III synthesis were significantly upregulated post-transformation. A tentative hypothesis is that under pathological conditions MKs may release TGF-β and other growth factors through a mechanism implicating emperipolesis and aberrant distribution of P-selectin, which can induce the production of collagen and reticulin by the fibrogenic cells. A recent study identified higher levels of the latent form of TGF-β1 on MKs of ET patients with myelofibrosis compared to controls.

**Mouse models of AMKL and Myelofibrosis**

Much of our knowledge regarding the role of MKs in myelofibrosis has been obtained through the use of mouse models. Currently, mouse models of AMKL, MPN and BM fibrosis do not recapitulate all aspects of the disease (discussed in). Characteristics of major models developed so far are reviewed here and a summary of all reported models is provided in Table 1.

In seminal studies mice infected with the Myeloproliferative Sarcoma Virus (MPSV) exhibited expanded splenic megakaryopoiesis accompanied by BM and spleen fibrosis. Enhanced TPO/MPL signaling is known to induce proliferation of MKs. Interestingly, in some cases, this proliferation is accompanied by reticulin deposition in BM. Transgenic mouse models of the TPO/MPL axis were based on the expression of TPO either downstream of the ApoE promoter along with a hepatic enhancer element, or downstream of the murine IgH promoter.
Although both models exhibited increase in MK and platelet numbers, for unclear reasons only the latter had developed myelofibrosis at nine months of age. It is noteworthy that the levels of TGF-β were elevated in the IgH promoter model; and rats treated with the TPO mimetic Romiplostin show BM fibrosis and an increase in MK number\textsuperscript{45}. Reticulin deposition (usually reversible) was also noted in some patients treated with TPO mimetic agents including Romiplostin\textsuperscript{45}. On the other hand, in experiments involving adenoviral-mediated expression of MPL, osteomyelofibrosis was not observed in NOD-SCID mice despite elevated numbers of MKs, implying that the development of BM fibrosis is a complex process requiring the synergy of other components of the BM niche\textsuperscript{46}.

Mutations of JAK2 are frequently detected in human MPNs. A knock-in mouse model of JAK2V617F exhibited splenomegaly with increased numbers of atypical BM MKs, accompanied by emperipolesis but without differences in MK ploidy compared to control mice\textsuperscript{47}. Intriguingly, although the knock-in JAK2V617F mice developed a rapidly lethal phenotype resembling PV, reticulosis was not observed even at terminal stage. By contrast, a conditional knock-in model of JAK2V617F exhibited a phenotype resembling PV and fibrosis of both spleen and BM\textsuperscript{48}. A number of transgenic mouse models encompassing the JAK2V617F with varying expression levels were also engineered\textsuperscript{49}. Phenotype varied depending on the level of JAK2V617F expression: where expression levels were lower than that of the wild-type JAK2, the phenotype resembled ET, while where the level approximated that of wild-type JAK2, the phenotype resembled PV. A BM transplantation assay\textsuperscript{50} of JAK2V617F in Balb/c and C57BL/6 mouse strains revealed reticulin fibrosis only in the BM of the former strain. Of note, MK proliferation with impaired differentiation was observed in both strains. In a different study\textsuperscript{51}, the murine JAK2V617F transplantation experiments induced a phenotype resembling MPN, and it was noted that fibrosis was associated with osteosclerosis. One study involving patients with MPN showed that the osteoclast number increased in advanced stages of the disease, while in a second study osteoclast number was low or normal regardless of disease stage\textsuperscript{52}.

A mutation of the TPO receptor (MPLW515L) was identified in a subset of patients suffering from MPN. Overexpression of the mutated receptor in BM cells of mice resulted in a rapidly lethal myeloproliferative disease with increased number of platelets and MKs (atypical and dysplastic), elevated white blood cell (WBC) count and reticulin fibrosis\textsuperscript{53}. A similar phenotype was observed in the BM transplantation model of the MPLT487A mutation, identified in a patient suffering from non-DS-AMKL\textsuperscript{54}. The MPLT487A transduced mice exhibited an increase
of MKs (CD41+/CD42+) in BM and spleen. In addition, transplanted mice exhibited elevated levels of platelets and WBC counts and myelofibrosis similar to that observed in MPLW515L. In the OTT-MAL knock-in mouse model, leukemia developed only in a small percentage of mice after a prolonged time interval55. However, overexpression of MPLW515L through retroviral transduction and transplantation resulted in a phenotype resembling AMKL, with BM fibrosis and a large number of megakaryoblasts infiltrating BM, spleen and liver.

Moreover, some exclusively experimental models are reported to induce phenotype similar to MPNs associated with myelofibrosis. For a complete list, please refer to Table 1. Notably, the GATA-1\textsuperscript{low} mouse model, in which the distal promoter of GATA-1 and the DNase hypersensitive region were abrogated, displayed myelofibrosis with a significantly increased number of MKs arrested between the stage of megakaryoblast and immature MK stages. An important element of this model is that although the minority of mice that survived gestation exhibited thrombocytopenia and anemia, the latter resolved within a few weeks56. These mice began developing myelofibrosis early, and the full presentation occurred at approximately 15 months of age; once myelofibrosis ensues, mice succumb within few months57. It is worth noting that expression of the PDGF gene was elevated in these mice compared to controls.

The Ts65Dn mouse strain is trisomic of 104 orthologs of human chromosome 21, and a widely used model of DS. These mice have a higher number of lower ploidy MKs in BM and spleen than wild-type mice58. Myeloproliferative disease can be detected by 4 months, and after the first year of life thrombocytosis and myelofibrosis develop in all mice. Neither GATA-1\textsuperscript{low} nor Ts65Dn mice progress to AMKL.

Taken together, several of these mouse models show a significant association between increased number of MKs and the development of an elaborate extracellular matrix typical of myelofibrosis. However, the etiology of phenotypical differences will require better understanding of the interplay between growth factors, MKs and components of the bone marrow niche.

**Current Therapies for Myelofibrosis**

Large clinical trials focusing on the treatment of MPN are limited, and treatments based on empirical reasoning are not uncommon. For ET and PV, the modalities currently in use59, which include Aspirin, Hydroxyurea, Busulphan, Chlorambucil and \textsuperscript{32}P, lack a specific molecular
target. A potential exception is Anagrelide, which was shown to inhibit MK polyploidization by a yet undiscovered mechanism. The management of myelofibrosis is a clinical challenge with grim prognosis. Stem cell transplantation, although potentially curative, is accompanied by significant mortality and morbidity.

Hence, it is not surprising that research is focused on modified/mutated genes in myelofibrosis patients. The discovery of the JAK2V617F mutation, although not fitting the BCR-ABL paradigm of the CML, drew attention to the development of targeted inhibitors of JAK2V617F. Several inhibitors are now in clinical trials with encouraging results, although myelosuppression and gastrointestinal side effects occur (recently reviewed in). Other approaches include inhibition of the mTOR/AKT pathway or Histone Deacetylase Complex. In addition, inhibitors of the BCL-2, BCL-XL, HSP90 and telomerase are under development. A brief account of some of the several clinical trials is given below.

An important study relating to JAK2 inhibitors is the Controlled Myelofibrosis Study with Oral JAK inhibitor Treatment (COMFORT). COMFORT was a multicenter, double blind, placebo-controlled study in which patients suffering from PMF or post-ET/PV myelofibrosis received the JAK1/2 inhibitor Ruxolotinib or placebo. The primary end point of the study, reduction of spleen size of at least 35% at 24 weeks, was reached by a significant proportion of patients (41.9%) on Ruxolotinib. In addition, the Ruxolitinib group exhibited a statistically significant improvement in their symptoms and in overall survival (median follow up of 51 weeks) compared to the placebo group. Side effects of Ruxolotinib were anemia, neutropenia and thrombocytopenia, and 2 patients progressed to Acute Myeloid leukemia. BM evaluation was not performed in this study.

A second study (COMFORT 2) compared Ruxolitinib to best available therapy (any commercially available therapy or no treatment at all, as judged individually for each patient). In this study, reduction of spleen size of at least 35%, as assessed by MRI or CT scan was the primary end point. Although no survival benefit or histomorphological changes of BM were noted, patients receiving Ruxolitinib exhibited statistically significant reduction in spleen size and in myelofibrosis-related symptoms. Anemia and thrombocytopenia were the most frequently reported hematological side-effects, while diarrhea and abdominal pain were also reported. Of note, data derived from use of Ruxolitinib in the JAK2V617F knock-in mouse model demonstrated a reduction in splenomegaly and erythroid hyperplasia but persistence of MPN-initiating population.
CEP-701 (Lestaurtinib) is another powerful JAK2 inhibitor with promising \textit{in vitro} results\cite{68}, used in a small phase 2 study of myelofibrosis patients harboring the JAK2V617F mutation\cite{69}. According to IWG-MRT criteria, overall response was 27\% and side-effects included anemia, thrombocytopenia, and gastrointestinal complains. However, the burden of JAK2V617 was not reduced and none of the patients had improvement in BM fibrosis.

IMiDs are immunomodulatory thalidomide analogues, used in the treatment of MDS\cite{70}. Some IMiDs have been tested in patients suffering from myelofibrosis. For example, Lenalidomide in conjunction with prednisone was studied in 40 patients with myelofibrosis\cite{71}. Response to anemia (30\%) and splenomegaly (42\%) was noted, and some of the patients had a significant reduction of fibrosis. Pomalidomide is another IMiD drug that has been used alone and in combination with prednisone in patients suffering from PMF. High doses of Pomalidomide were associated with heightened side effects. In a multicenter study, low doses of Pomalidomide, used as a single agent, or combined with a short course of prednisone, ameliorated myelofibrosis-related anemia\cite{72}.

\textbf{Lysyl oxidase (LOX) in MK-Induced Fibrosis: a Potential Therapeutic Target}

LOX is a copper-dependent enzyme that cross-links collagen or elastin by oxidative deamination of peptidyl lysine or hydroxylysine and peptidyl lysine residues, respectively, and contributes to the accumulation of extracellular matrix by promoting intra and interpeptide chain crosslinking\cite{73}. LOX is produced by fibrogenic cells and is secreted as a 50 kDa glycosylated pro-enzyme. BMP-1, which is also expressed in MKs\cite{74}, cleaves the LOX pro-enzyme extracellularly to release the 18 kDa propeptide and the mature 32 kDa LOX enzyme. A recent study showed LOX expression in low ploidy, proliferating MKs, and its scarce expression in mature MKs of normal mice\cite{75}. LOX was also abundant in the GATA-1\textsuperscript{low} mouse model with pathologically high levels of low ploidy MKs associated with an extensively fibrotic matrix\cite{75}. LOX enzymatic activity is inhibited irreversibly by \(\beta\)-aminopropionitrile (BAPN), which has been used in animal models in the context of tissue fibrosis or metastasis\cite{76}. Intriguingly, administration of BAPN to GATA-1\textsuperscript{low} mice, which show an abundance of proliferating MK in BM and myelofibrosis, inhibited the progression of myelofibrosis, linking, for the first time, BM fibrosis and production of LOX by low ploidy MKs\cite{75} (Figure 1). Although the potential role of LOX in myelofibrosis was only tested on the GATA-1\textsuperscript{low} mouse model, these results could serve as a primer for further pre-clinical or clinical studies.
BAPN is a lathyrogen, the toxic constituent of peas from *Lathyrus* plants. Lathyrysm, a disease known for centuries, encompasses two distinct entities: a disorder of the nervous system (neurolathyrysm) leading to limb paralysis, and a disorder of connective tissue, causing either bone deformity (osteolathyrysm) or aortic aneurisms (angiolathyrysm). BAPN, the toxic principle of *L. odoratus*, causes osteolathyrysm and angiolathyrysm when ingested in large quantities. BAPN has been used in small scale clinical trials in patients suffering from scleroderma, urethral strictures, keloids or undergoing tendon repair. BAPN was not effective in a study of 10 patients suffering from scleroderma, and anemia, allergic rash, and a case of bone deformity were reported with the dosage and regime used. In a study of patients undergoing flexor tendon repair, all six patients developed side-effects that included fever, periportal hepatitis, skin rash and gastrointestinal symptoms. Side effects rapidly resolved following discontinuation of BAPN with no long-term consequences. On the other hand, one gram per day of BAPN was shown to be effective in 9 patients affected with keloids who received it for a total of 21 days without report of adverse effects. Furthermore, in a study of patients undergoing flexor tendon repair, all six patients developed side-effects that included fever, periportal hepatitis, skin rash and gastrointestinal symptoms. Side effects rapidly resolved following discontinuation of BAPN with no long-term consequences. On the other hand, one gram per day of BAPN was shown to be effective in 9 patients affected with keloids who received it for a total of 21 days without report of adverse effects. Larger studies are required to determine optimal dose and safety profile.

The functions attributed to LOX have recently been expanded; LOX oxidizes the PDGF receptor on smooth muscle cells, fibroblasts, and MKs and enhances the proliferation signaling from this cytokine, leading to higher cell number. Thus, LOX is capable of enhancing the proliferation of low ploidy MKs, which in turn produce LOX that further stabilizes the matrix resulting in a fibrotic phenotype (Figure 2).

In response to the differential expression of LOX within the MK lineage, and the effect of LOX on matrix deposition, LOX gene expression has been a focus of study. The LOX gene is mapped on human chromosome 5q23 and its expression (reviewed in) is closely linked to that of collagen. For example, a putative binding site has been recognized for the CCAAT binding factor, an inducer of collagen synthesis in the Rat LOX promoter. Moreover, HIF-1a is a potent modulator of LOX expression. In addition, growth factors such as PDGF and TGF-β1, and the cytokine interleukin 1b increase expression of LOX expression. This is of interest also in the context of MKs, since pathological states involving expansion of MKs also lead to increased levels of extracellular factors, such as PDGF and TGF-β1, which in turn have the potential to further boost the fibrotic phenotype.
While this review focuses on LOX and BM fibrosis, a number of reports support the involvement of LOX in various other pathologies. LOX was detected by microarray studies in the BM blasts of 9/11 patients suffering from non DS-AMKL, contributing to a specific gene profile (raw data deposited at www.ncbi.nlm.nih.gov/geo; GEO accession number GSE4119). LOX has been intensely studied in the context of solid tumors\textsuperscript{89}. LOX was originally identified as a suppressor of RAS transformation in NIH3T3 cells, and its gene expression is downregulated in several carcinomas\textsuperscript{90}. LOX has also attracted attention in the context of metastasis\textsuperscript{76}.

Of note, LOX-like proteins (LOXL1-4) have been described that share the LOX catalytic site. LOXL1 is structurally most closely related to LOX and pattern of expression those two genes overlap in many tissues. LOXL1 knockout mice are viable but display defects predominantly in tissues with high elastin content such as lung, skin and uterus. By contrast, LOXL2, 3 and 4 have a different, less diverse, gene expression pattern and share four Scavenger Receptor Cysteine Rich (SRCR) regions. LOXL2 is associated with development of aneurysms and is overexpressed in fibrotic lung and liver tissues\textsuperscript{91}. An antibody against LOXL2 was shown to ameliorate organ fibrosis in mouse models of lung and liver fibrosis\textsuperscript{92}. Currently, the humanized version of the antibody (GS-6624, former AB0024) is in Phase 2 clinical trial to evaluate efficacy in adult myelofibrosis (ClinicalTrials.gov identifier: NCT01369498). LOXL3 expression was detected in placenta, heart and breast and, importantly, in highly malignant breast cancer cells\textsuperscript{91}. In the context of megakaryopoiesis, upregulated LOXL3 gene expression has been reported during endomitosis\textsuperscript{93}, and the LOXL3 protein was detected in human platelets\textsuperscript{94}.

Although the focus of this review is the importance of megakaryocytes in the progression of myelofibrosis, it is important also to consider the involvement of cells from other lineages. LOX is expressed in lineages populating the BM niche. Osteoblastic differentiation is impaired in LOX knockout mice\textsuperscript{95}. LOXL2 also controls angiogenesis in the endothelial basement membranes\textsuperscript{96} and LOX is expressed in fibroblasts (discussed in \textsuperscript{88}). One can readily envision a state of pathological levels of MKs leading to increased secretion of PDGF or TGF-\(\beta\), which in turn are capable of increasing fibroblast proliferation, in addition to LOX-induced matrix deposition.

**Perspective:** The control of fibrosis could be a potential therapeutic target for conditions such as AMKL and a subset of MPN, especially PMF. Current therapies have had limited success and
the recent model linking MK-induced myelofibrosis to LOX suggests promise in the use of LOX inhibitors for controlling BM fibrosis.

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### Table 1: Mouse models of AMKL and Myelofibrosis

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<tr>
<td>AMKL: acute megakaryoblastic leukemia</td>
<td>Myelofibrosis after the first year of life</td>
<td>The Ts65Dn mouse strain Induced translocation resulting in segmental trisomy of distal chromosome 16</td>
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<tr>
<td>Bach1</td>
<td>Transgenic</td>
<td>GATA-1 promoter drives expression; Bach1 mutation has not been reported in MPN.</td>
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<tr>
<td>NF-E2 overexpression.</td>
<td>Transgenic</td>
<td>Abnormally clustered MKs; increased deposition of collagen and reticulin.</td>
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**Abbreviations:**

AMKL: acute megakaryoblastic leukemia; BM: bone marrow; MPN: myeloproliferative neoplasms; PV: polycythemia vera; ET: essential thrombocythemia; MKs: megakaryocytes;
Figure Legends

Figure 1: Effect of LOX inhibition on marrow fibrosis in vivo. A. representative hematoxylin & eosin (H&E, left column) and Gomori silver (right column) staining of longitudinal sections of femurs from wild-type and GATA-1<sup>low</sup> (male littermates), control, or BAPN-treated mice (10.5 weeks old at the time of collection). Original magnification for the left column was 400× and for the right column are 600×. Arrows indicate the large presence of MKs (H&E stain) and the accumulation of reticulin fibers in the GATA-1<sup>low</sup> mice. B. quantification of fibrosis in BAPN or vehicle-treated GATA-1<sup>low</sup> mice. Fibers were measured in arbitrary units from stained sections. Data are represented as absolute values (top panel) or as mean percent change compared with values recorded from vehicle-treated GATA-1<sup>low</sup> mice (bottom panel). The mean values were obtained from five mice per group. Scale bars (10 μm) are at the upper left corner of each column. Results are presented as absolute values and percentage change; n = 5; *, p < 0.05. This figure was originally published in 75. © American Society for Biochemistry and Molecular Biology.

Figure 2: Possible mechanisms of contribution of LOX to progression of myelofibrosis. Low ploidy MKs have elevated levels of expression of LOX, which is secreted to the bone marrow microenvironment. The active LOX enzyme promotes cross-linking of matrix collagen and consequent fiber deposition. The active LOX enzyme also oxidizes the PDGF receptor, enhancing the proliferative response from this receptor. Inhibition of LOX by BAPN may reverse this process. High ploidy MKs express very low amounts of LOX. LOX: lysyl oxidase; BM: bone marrow; BAPN: β-aminopropionitrile; PDGF: platelet-derived growth factor; MKs: megakaryocytes.
Figure 1

A.  

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B.  

**FIBERS**

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% Change

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Figure 2

Fibrosis

Low ploidy MKs

Proliferation

BM matrix cross-linking

LOX ↑

Oxidation of PDGF receptor

Ploidy

LOX ↓

High ploidy MKs
Megakaryocyte pathology and bone marrow fibrosis: the lysyl oxidase connection

Nikolaos Papadantonakis, Shinobu Matsuura and Katya Ravid