

Hematological disorders and pulmonary hypertension

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Abstract

Pulmonary hypertension (PH), a serious disorder with a high morbidity and mortality rate, is known to occur in a number of unrelated systemic diseases. Several hematological disorders such as sickle cell disease, thalassemia and myeloproliferative diseases develop PH which worsens the prognosis. Associated oxidant injury and vascular inflammation cause endothelial damage and dysfunction. Pulmonary vascular endothelial damage/dysfunction is an early event in PH resulting in the loss of vascular reactivity, activation of proliferative and antiapoptotic pathways leading to vascular remodeling, elevated pulmonary artery pressure, right ventricular hypertrophy and premature death. Hemolysis observed in hematological disorders leads to free hemoglobin which rapidly scavenges nitric oxide (NO), limiting its bioavailability, and leading to endothelial dysfunction. In addition, hemolysis releases arginase into the circulation which converts L-arginine to ornithine, thus bypassing NO production. Furthermore, treatments for hematological disorders such as immunosuppressive therapy, splenectomy, bone marrow transplantation, and radiation have been shown to contribute to the development of PH. Recent studies have shown deregulated iron homeostasis in patients with cardiopulmonary diseases including pulmonary arterial hypertension (PAH). Several studies have reported low iron levels in patients with idiopathic PAH, and iron deficiency is an important risk factor. This article reviews PH associated with hematological disorders and its mechanism; and iron homeostasis and its relevance to PH.

Key words: Anemia; Hemolysis; Iron homeostasis; Myelofibrosis; Pulmonary hypertension

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Core tip: Oxidant injury, inflammation, impaired nitric oxide bioavailability and coagulopathy that

occur in hematological diseases lead to endothelial dysfunction and thrombo-embolism with subsequent development of pulmonary hypertension (PH). In addition, treatment used for these disorders such as immunosuppressive drugs, splenectomy, bone marrow transplantation and radiation therapy are also known to cause endothelial damage and thrombo-embolism leading to PH. Furthermore, there is a causal relationship between vascular and hematopoietic systems. Patients with chronic myeloproliferative diseases are at a risk of developing PH; and the occurrence of myelofibrosis contributing to impaired hematopoiesis is not uncommon in PH.

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INTRODUCTION

Pulmonary hypertension (PH) is a devastating sequela of a number of diverse systemic diseases including cardiopulmonary, autoimmune, inflammatory and myeloproliferative diseases, drug toxicity, acquired immunodeficiency syndrome, portal hypertension, and hemolytic anemia. Based on the clinical diagnosis, PH is classified into 5 major groups, which was updated in 2013^[1]. Group 1 is labeled pulmonary arterial hypertension (PAH). Included in this group are idiopathic and heritable PAH, PAH associated with human immunodeficiency viral infection, schistosomiasis, congenital heart defect, connective tissue diseases, portal hypertension and drug-induced PAH. In the current updated classification, PH associated with hematological disorders, myeloproliferative diseases and splenectomy has been moved to Group 5. Pulmonary veno-occlusive disease (PVOD)/pulmonary capillary hemangioma and persistent PH of the newborn are in Group 1 as subcategories (1' and 1'' respectively). Group 2 comprises PH associated with congenital and acquired left heart diseases, Group 3 includes PH due to lung diseases and/or hypoxia, Group 4 includes chronic thromboembolic pulmonary hypertension (CTEPH). PH associated with hematological disorders, myeloproliferative diseases, splenectomy and a number of miscellaneous systemic and metabolic disorders are included in group 5. PH is defined as a mean pulmonary artery (PA) pressure of ≥ 25 mmHg at rest as measured by cardiac catheterization. Right heart catheterization is considered the gold standard for the diagnosis of PH. Echocardiography is a useful noninvasive tool to estimate right ventricular systolic pressure (in the absence of right heart obstruction) for screening and monitoring the patients with PH^[2].

Pulmonary vascular endothelial injury/disruption is

considered to be an important initiating factor in the development of PH. The severity, the extent and the site of endothelial damage may determine the type of PH and the irreversibility of the disease. Endothelial cells (EC), a non-thrombogenic monocellular layer function as an interface between the circulating blood and the underlying tissue. EC produce vasorelaxants such as nitric oxide (NO), prostacyclin, and endothelium-derived hyperpolarizing factor. In addition, EC inhibit cell proliferation, and participate in inflammation, thrombosis, barrier function, cell cycle and apoptosis; EC control vascular tone and structure, maintain homeostasis, thus, participate in vascular pathobiology. NO, generated from L-arginine by catalytic activity of endothelial NO synthase (eNOS) in vascular EC is a short-lived free radical; it stimulates soluble guanylate cyclase that catalyzes guanosine triphosphate to cyclic guanosine monophosphate (cGMP). Increase in cGMP results in a decrease in Ca^{2+} levels that mediates NO functions including vascular relaxation^[3]. eNOS is localized in special cellular domains in EC including Golgi bodies and plasmalemmal caveolae, and is tightly regulated by a variety of transcriptional, post-transcriptional and post-translational mechanisms. The proteins that modulate the eNOS activity include caveolin-1, heat shock protein 90, cationic amino acid transporter 1 (arginine transporter), Ca^{2+} -calmodulin, and others. Caveolin-1 is a scaffolding protein of caveolae found on the plasma membrane of a variety of cells including EC, smooth muscle cells (SMC) and fibroblasts. Caveolin-1 interacts with transducing molecules in caveolae and maintains these molecules in an inhibitory state. It has a dynamic relationship with eNOS. In EC, caveolin-1 inhibits NO signaling by binding to eNOS. In response to various stimuli, eNOS is dissociated from caveolin-1, and generates NO. However, caveolin-1 is essential for agonist-induced eNOS activation^[3,4]. In addition, the eNOS activity is controlled by endogenous circulating inhibitors; the most important being the L-arginine analog, asymmetric dimethylarginine (ADMA). ADMA inhibits eNOS-mediated production of NO from L-arginine. A large portion of circulating ADMA is metabolized by dimethylarginine dimethylaminohydrolase (DDAH) to L-citrulline and dimethylamine. DDAH is inhibited by oxidative stress, thereby leading to ADMA accumulation and resulting EC dysfunction^[5]. Recent studies have shown that erythrocytes take up and store ADMA. Following lysis of erythrocytes, proteolysis of methylated proteins generate free ADMA which then can inhibit NO production leading to EC dysfunction, and contribute to vascular disease^[6]. In a group of 34 healthy individuals (age 2 d-24 years), plasma levels of ADMA has been shown to decrease with age^[7].

Hemolysis is a common occurrence in a number of hematological disorders. Released free hemoglobin (Hb) as a result of hemolysis reacts with NO and forms inactive nitrate and methemoglobin, thus leading to endothelial dysfunction. In addition, arginase 1 released

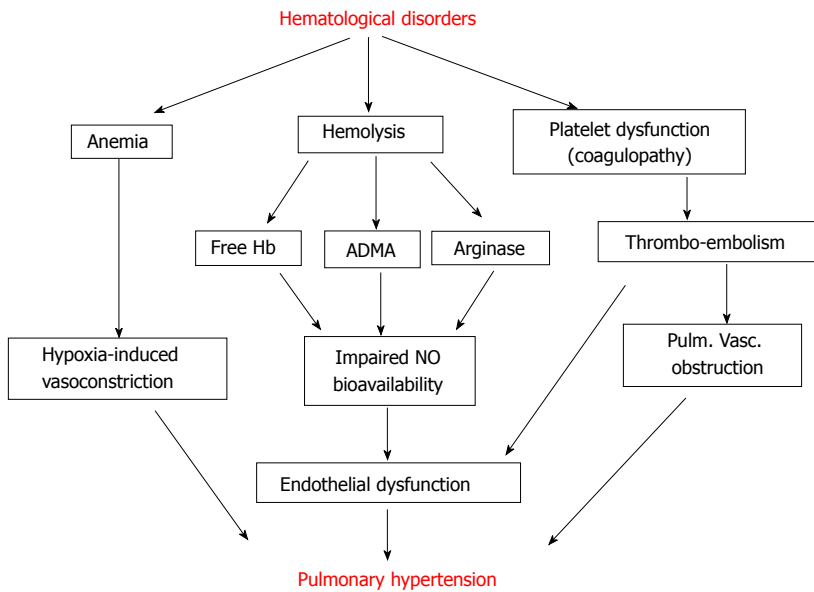


Figure 1 Various pathways of hematological disturbances leading to pulmonary hypertension. ADMA: Asymmetric dimethylarginine; Hb: Hemoglobin; NO: Nitric oxide; Pulm. Vasc.: Pulmonary vascular.

during hemolysis alters arginine metabolism, further reducing NO bioavailability^[8,9]. Arginase 1 converts L-arginine to ornithine, a precursor of proline. Proline is an amino acid involved in collagen formation, lung fibrosis and SMC proliferation. Low arginine/ornithine ratio has been reported to be associated with high mortality. Under conditions of low arginine and tetrahydrobiopterin, eNOS is uncoupled generating reactive oxygen species^[10]. These changes lead to pulmonary vascular remodeling and increased pressure. Furthermore, therapeutic measures used in patients with hemolytic disorders have been shown to be associated with PH^[11]. Figure 1 depicts the alterations observed in hematological disorders that can lead to PH.

Iron is an essential trace element required for a number of biological processes including cellular response to hypoxia, cell proliferation, immune responses and mitochondrial function. It also has the ability to generate free radicals, which cause deleterious effects. Mitochondria use iron for heme synthesis and in iron-sulfur cluster biogenesis. Hcpidin expressed in the liver is thought to be a key regulator of iron homeostasis. Dietary iron is absorbed through the duodenal enterocytes and exported to circulation *via* ferroportin, an iron transporter. Increased levels of hepcidin degrade ferroportin, thus inhibit iron uptake; whereas low levels allow increased iron absorption. Hcpidin is upregulated by BMP6, and inflammatory cytokines including IL-6, IL-1 β through JAK2/STAT3 pathway. It is downregulated by iron deficiency, erythropoiesis and hypoxia in order to increase iron levels. Major portion of iron is in erythroid marrow, and erythropoiesis is the major regulator of hepcidin. Erythropoiesis releases erythroferrone that in turn inhibits hepcidin transcription to increase iron absorption. Excess intracellular iron is stored by ferritin that prevents iron-mediated free radical formation^[12-15]. Iron circulates bound to a glycoprotein, transferrin, which keeps it soluble; iron is delivered into cells through transferrin receptor (TfR1)^[16]. Physiological

iron saturation range for transferrin is 20%-45%. Less saturation is indicative of iron deficiency and saturation above 80% is associated with non-transferrin-bound iron which has toxic effect on the tissue^[17]. Intracellular iron regulates TfR1 *via* iron responsive elements that are recognized by iron regulatory proteins (IRPs) which bind to iron responsive elements of TfR1, and prevent degradation when the intracellular iron levels are low. Increased cellular iron levels inactivate IRP1 resulting in degradation of TfR. Furthermore, IRP1 and IRP2 are required for mitochondrial iron supply and function^[18,19]. Deregulation of iron homeostasis plays an important role in the pathophysiology of hematological disorders and several cardiovascular diseases including PAH. Deregulated iron metabolism can result in iron overload as seen in some of the hematological disorders leading to toxic effects, or to deficiency as seen in anemia. Several recent studies have reported low iron levels in patients with idiopathic PAH, that is considered to be an important risk factor^[20].

HEMATOLOGICAL DISORDERS AND PH

Persistent pulmonary hypertension of the newborn associated with anemia

Persistent pulmonary hypertension of the newborn (PPHN) is the result of failure of cardiopulmonary transition at birth. It is associated with cardiovascular anomalies, meconium aspiration syndrome, lung hypoplasia, sepsis, respiratory distress syndrome, or it could be idiopathic. In addition, maternal factors such as diabetes, obesity, elective cesarean section; and maternal drug use such as aspirin, nonsteroidal inflammatory agents and serotonin reuptake inhibitors are known to be associated with PPHN. The incidence of PPHN is about 1.9 per 1000 live births, and the mortality is reported to be 10%. The major findings of PPHN are elevated pulmonary artery pressure, right to left shunt at the foramen ovale or at the ductus level, and

hypoxemia^[21,22]. Recent studies have shown that PPHN can also be associated with severe neonatal anemia. However, anemia as a potential cause of PPHN is not well recognized. In a series of 12 infants, 7 were reported to have congenital dyserythropoietic anemia; and three with ϵ - γ - δ β -thalassemia, one with HbH disease and another one with Diamond-Blackfan anemia^[23]. Another report described 3 siblings with dyserythropoietic anemia and PPHN. Two infants survived after blood transfusion, oxygen; and one infant in addition, had received inhaled NO^[24]. Others have reported PPHN associated with anemia; one infant with fetal anemia associated with maternal trophoblastic tumor, two infants with fetal anemia due to massive fetomaternal hemorrhage and in the fourth case the reason for anemia was not known. All these infants had received blood transfusion for anemia^[25,26]. In addition, neonates with twin-to-twin transfusion syndrome are at a risk of developing PPHN^[27]. The reason for PPHN associated with anemia is not clear. Hypoxia secondary to low Hb level could be a contributing factor to PPHN. Interestingly, booster packed red blood cells (RBCs) transfusion has been shown to improve tissue oxygenation in premature infants^[25,28]. The increase in plasma Hb levels following transfusion could be an additional factor contributing to high pulmonary artery pressure. Cell-free Hb scavenges NO, thus, leading to vasoconstriction and increased pulmonary artery pressure. Experimental studies have shown transient increase in pulmonary artery pressure following blood transfusion^[29]. Furthermore, transfusion with aged stored blood results in increased cell free plasma Hb levels, higher levels of arginase, endothelial dysfunction and increased pulmonary artery pressure^[30,31]. Recently, significant reduction in flow-mediated dilatation was reported in adult patients who received old blood (> 21 d) compared with the ones who received fresh blood (< 14 d old)^[32]. Inhaled NO prevents the elevation of pulmonary artery pressure induced by aged blood transfusion^[31,32]. The possibility of PPHN needs to be considered in the presence of severe anemia in newborns. In addition to blood transfusion, inhaled NO may be necessary to ameliorate PH.

Hemolytic disorders and PH

Hb disorders include sickle cell disease and thalassemia; and RBC membrane diseases include spherocytosis, stomatocytosis and paroxysmal nocturnal hemoglobinuria. PH is one of the leading causes of morbidity and mortality in patients with hemolytic disorders. Major causes of PH in hemolytic disorders are hemolysis, hypercoagulability and iron overload resulting from transfusions and splenectomy^[9,33-35]. Recently, in a murine model of hemolysis, significant reduction in NO bioavailability due to free Hb was shown to be accompanied by platelet activation and the activation of coagulation pathway resulting in thrombosis, PH, right ventricular failure and death. Interestingly, treatment with sildenafil reduced the mortality rate^[36]. Furthermore, Hb has been shown to interact with

superoxide and hydrogen peroxide, thus increasing reactive oxygen species formation, lipid peroxidation, and increase inflammatory response. Interestingly, in an experimental model, treatment with haptoglobin, a Hb scavenger was shown to decrease oxidative and inflammatory response and attenuate PH^[37]. Free Hb plays a significant role in the pathogenesis of PH in hemolytic disorders; therefore, treatment with Hb scavengers appears to be an attractive therapeutic option.

Sickle cell disease: Hb in patients with sickle cell disease (SCD) is structurally different; valine is substituted for glutamic acid in the 6th position of β -globulin subunit of Hb^[38]. This mutation produces abnormal and insoluble HbS. The major genotypes of SCD are homozygous SS, heterozygous SC and S/ β thalassemia. In the United States, 0.15% of African-Americans are homozygous for SCD, and 8% have sickle trait. SCD is characterized by anemia, severe pain, potentially life-threatening complications such as bacterial sepsis, splenic sequestration, acute chest syndrome, stroke, chronic organ damage resulting from chronic hemolysis and intermittent ischemia. Vasculopathy in SCD results in irreversible organ damage, a frequent cause of death beyond childhood. Recent studies have shown that chemically-induced RBC stiffness leads to increased pulmonary artery pressure and pulmonary vascular resistance^[39]. Importantly, sickled RBCs are stiffer than controls^[40], which may partly contribute to PH in SCD. Furthermore, RBCs from SCD patients have an abnormal tendency to adhere to vascular endothelium. This abnormal adhesion plays an important role in facilitating the trapping of sickle cells in post-capillary venules and causing vascular obstruction which is the underlying factor for the characteristic features of SCD such as painful vascular occlusive crises and acute chest syndrome. In addition, the sickle cell adherence to EC results in the activation of EC and a chronic state of inflammation. Endothelial activation is a critical component of the microvascular responses accompanying SCD resulting in inflammatory response, increased expression of cell adhesion molecules and reactive oxygen species, and altered vasomotor tone leading to vasculopathy including PH. Interestingly, hypoxia/reperfusion injury causes inflammatory response in sickle cell transgenic mice^[41-43].

Morbidity and mortality in SCD are high, and PH is a serious complication in SCD. Sudden death in patients with SCD and PH is not uncommon^[44,45]. In a small series of autopsy cases (12 patients), 75% of patients had right ventricular hypertrophy and 50% revealed large thrombus in pulmonary artery, and 40% exhibited pulmonary vascular remodeling. The mortality in patients with catheterization-confirmed PH is 50% within 2 years compared to 7% at 10 years in SCD patients without PH^[46-49]. In adult population with SCD, echocardiography revealed high incidence of PH (27%) as assessed by a tricuspid regurgitation jet velocity

(TRJV) of > 2.5 m/s, however, the incidence was confirmed to be 6%-10% by cardiac catheterization, and > 50% of these patients had post-capillary PH^[50-52]. A recent study showed increased TRJV in children to be associated with an increased PA pressure, increased cardiac output due to anemia and normal pulmonary vascular resistance^[53]. The incidence of PH in patients with SCD, however, is relatively high (6%-10%), compared with the normal population (2.4-7.6 people/million per year). It is noteworthy that SCD patients with lower pulmonary artery pressure are at a higher risk compared with idiopathic PAH with equivalent pressure. Recent experimental studies in rodents reveal that it is the Hb-induced inflammation and to a lesser extent the Hb-induced oxidant injury leads to vascular injury^[54]. Thus, RBC sickling, rheological abnormalities, hypoxemia, heme-induced oxidant injury and resulting inflammatory response leading to endothelial dysfunction play a major role in vasculopathy leading to vaso-occlusive disease including PH.

Thalassemia: Thalassemia diseases are an inherited Hb disorders associated with chronic anemia, impaired erythropoiesis and dysregulated iron metabolism; resulting from defective synthesis of α and β subunits of HbA. Absence or impaired production of α globulin results in β thalassemia and vice versa. PH is quite rare in α thalassemia. β thalassemia is characterized by impaired erythropoiesis and dysregulated iron metabolism. Two types of β thalassemia have been described; thalassemia major (TM) and thalassemia intermedia (TI). Patients at birth are asymptomatic because of the presence of HbF. Diagnosis of TM is usually made during infancy because of anemia. They require frequent transfusion and chelation therapy which have improved their survival. Furthermore, well transfused patients with TM are at a lower risk of developing PH. In contrast, the TI patients remain transfusion-independent for a longer period; the incidence of PH is higher in this group^[34,55-57]. Pathophysiology of PH in thalassemia is similar to other hemoglobinopathies. Chronic hemolysis, iron overload, splenectomy, hypercoagulability, vascular inflammation and left ventricular dysfunction contribute to the pathogenesis of PH. Dysregulated arginine metabolism^[58] and elevated levels of ADMA^[59] have been reported in patients with β -thalassemia associated with PH. Higher incidence of PH was noted in patients with E/ β -thalassemia who had more severe hemolysis and had had splenectomy; in addition, inflammatory markers were increased^[60]. Increased non-transferrin bound iron and increased transferrin saturation indicative of iron overload increase the risk of cardiopulmonary damage^[61]. Interestingly, in a mouse model of β thalassemia, transferrin treatment normalized labile plasma iron levels and RBC survival, and increased hepcidin expression^[62]. In addition, increased hepcidin levels were accompanied by increased BMP2 expression in the liver and concomitant decrease in extracellular-signal related kinase (ERK) activation^[63].

Compared to β thalassemia, SCD patients do not have iron overload. This difference is thought to be due to the presence of chronic inflammation in SCD which could block iron release from reticulo-endothelial system. In addition, unlike SCD, hepcidin levels are low in β thalassemia, which can further enhance iron absorption^[64]. In β thalassemia, transfusion not only improves anemia but also suppresses erythropoiesis and increases hepcidin levels^[65]. Globin chain imbalance leads to ineffective erythropoiesis, and erythroferrone suppresses hepcidin production during increased erythropoiesis, resulting in low hepcidin levels and increased iron absorption. In a mouse model of β -thalassemia, ablation of erythroferrone restored hepcidin expression and reduced iron accumulation without affecting anemia^[66]. Furthermore, thalassemia carriers have been reported to have abnormal iron metabolism^[67].

RBC membrane disorders: RBC membrane-associated abnormalities are found in inherited disorders such as spherocytosis and stomatocytosis. A defect in one or several proteins such as ankyrin, spectrin (α and β), band 3 has been reported. Paroxysmal nocturnal hemoglobinuria (PNH) is an acquired RBC membrane defect. RBCs play a role in regulating membrane properties to undergo reversible deformation while maintaining integrity. In addition, RBCs have a pivotal role in regulating cell volume homeostasis. Inability to regulate cell volume is a feature of hemoglobinopathies^[68-70].

Hereditary spherocytosis (HS) is considered not to be associated with thrombo-embolic risk. In a recent study, 26 children who underwent splenectomy, no evidence of PH or coagulation defect was observed during a follow-up period of median 4.5 years^[71]. In another study that included 36 patients with HS (28 with splenectomy and 8 without), no evidence of PH was found^[72]. However, arterial and venous thrombo-embolic events in patients with HS have been observed after splenectomy^[73]; and several cases of CTEPH have been reported in patients with HS several years after splenectomy^[74-76]. In a review of 22 patients with CTEPH following splenectomy, 3 patients with HS had had splenectomy 17-35 years before the diagnosis of CTEPH was made^[77].

In hereditary stomatocytosis, the RBC membrane shows a leak of univalent cations (Na^+ and K^+). Two clinical variants have been recognized; hydrocytosis (overhydrated) and xerocytosis (dehydrated). Stewart *et al*^[78] described 11 patients with stomatocytosis after splenectomy. Most of them had thrombo-embolic episodes, and 3 of them developed PH. Other case reports have described PH in patients with stomatocytosis several years (approx 6-30 years) after splenectomy. One patient underwent successful pulmonary endarterectomy for CTEPH. He had undergone splenectomy as a child because of the family history of spherocytosis^[79]. Another patient with dehydrated hereditary stomatocytosis underwent

splenectomy because of splenic infarct following air travel. Approximately 12 years later she developed CTEPH. Because of the worsening condition she underwent successful heart-lung transplantation^[80]. The third case of stomatocytosis had splenectomy done for traumatic rupture of the spleen. About 6 years later he developed PH^[81]. Splenectomy is not recommended for stomatocytosis, however, stomatocytosis is often mistaken for spherocytosis, and splenectomy is performed. At times it is difficult to distinguish RBC morphology; therefore, intracellular electrolyte measurements or flux studies may be required to make the correct diagnosis^[78].

PNH is a progressive hemolytic disorder. It is an acquired clonal genetic deficiency of glycosylphosphatidylinositol-linked protein on the RBC surface that leads to complement-mediated hemolysis^[35,82]. One case of PNH was diagnosed to have PH 5 years after splenectomy and associated chronic thrombo-embolism^[83]. In one study, 41% patients with PNH and associated hemolysis (total 29 patients) had echocardiographic evidence of PH. Treatment with eculizumab reduced hemolysis^[82,84]. In another study, 23 patients with PNH and hemolysis were examined before and after eculizumab therapy. Importantly, markers of endothelial dysfunction (sVCAM1, vWF) and coagulation activation were significantly reduced after eculizumab therapy^[85].

Chronic myeloproliferative diseases and PH

Evidence is accumulating to suggest a link between PH and chronic myeloproliferative diseases (CMPD). CMPD originate in multipotent hematopoietic progenitor cells that are characterized by increases in one or more types of blood cells. CMPD include polycythemia vera, essential thrombocythemia, idiopathic myelofibrosis and chronic myeloid leukemia (CML)^[86]. Dingli *et al.*^[87] examined 26 patients with CMPD and echocardiography based diagnosis of PH (estimated systolic pulmonary artery pressure 35-100 mmHg); 24 patients had symptoms related to PH and 4 had had splenectomy. The mortality rate among these patients was high. Another report^[88] described 6 patients with myeloproliferative disease who developed PH (echocardiographic diagnosis, and in 4 confirmed with cardiac catheterization), and all had had splenectomy; 5 patients died within 1-6 mo of PH diagnosis. Lung histology in 3 patients revealed pulmonary myeloid metaplasia and fibrosis. A 72-year-old patient developed PH, right ventricular failure and thrombocytosis after splenectomy. The peripheral blood smear revealed megakaryoblasts. Interestingly, treatment with hydroxyurea not only decreased the platelet counts but also improved right heart failure. It was considered possible that megakaryocytes created obstruction in the pulmonary capillaries leading to PH^[89]. In a group of 30 patients with a past history of thromboembolism, high incidence of valve disease (aortic and mitral valve with vegetation) was noted; 13% of patients had PH secondary to venous obstruction^[90]. In

another study, 46 patients with essential thrombocytosis were compared with 40 patients with reactive thrombocytosis secondary to anemia. In the essential thrombocytosis group, elevated platelet levels and 43% thrombo-embolic events were recorded; and 47.8% (22/46) had echocardiographic evidence of PH. In contrast, the reactive thrombocytosis secondary to anemia group did not have increased platelet levels, thrombo-embolic events or PH^[91]. Garypidou *et al.*^[92] reported incidence of PH by echocardiography to be 41.7% in 24 patients with CMPD. In another report, among 103 patients with various CMPD, echocardiographic diagnosis of PH was made about 15 mo after the initial diagnosis of CMPD. The incidence of PH was found in less than 5%^[93]. A 50 years old individual was diagnosed to have PH (confirmed by cardiac catheterization) 15 years after the diagnosis of latent myeloproliferative disorder and portal hypertension. Portal hypertension is a known complication of CMPD^[94]. PVOD also has been reported in CMPD. A patient with myeloproliferative and myelodysplastic syndrome was treated with hydroxyurea for 4 years. Because of refractory thrombocytosis and hydroxyurea-induced neutropenia, anagrelide was started. Six weeks later, the patient was admitted with severe dyspnea at rest and was diagnosed to have PVOD^[95]. Guilpain *et al.*^[96], reviewed 10 cases of CMPD (8 polycythemia vera and 2 essential thrombocythemia) and PH; 6 patients developed CTEPH and 4 patients had PAH. Importantly, CTEPH occurred early in the course of the disease and PAH occurred several years after the diagnosis of CMPD. All patients with PAH revealed myeloid metaplasia but none in the CTEPH group.

The patients with CMPD are at a risk of developing PH; and the occurrence of myelofibrosis in patients with PAH is not uncommon and is thought to contribute to impaired hematopoiesis. Popat *et al.*^[97] reported moderate to severe myelofibrosis in 14/17 patients with PAH. However, platelets and granulocytes in PAH patients were polyclonal unlike monoclonal cells that were found in patients with polycythemia vera and essential thrombocythemia. Erythropoietin facilitates erythroid lineage and proliferation. Erythropoietin has also been shown to induce tyrosine phosphorylation of JAK2 and to associate with it for biological activities including mitogenesis^[98]. In a number of patients with CMPD, an acquired somatic *JAK2V617F* mutation has been observed, which confers a selective growth advantage. Interestingly, a small molecule inhibitor of JAK2 has been shown to attenuate myeloproliferative disease in a mouse model^[99,100]. However, the patients with PAH (13 Familial PAH, 24 Idiopathic PAH, and 15 Associated PAH) and the controls did not reveal JAK2 mutation^[101], nor was the JAK2 mutation noted in 19 patients with myelofibrosis secondary to PH^[102]. Circulating CD34⁺CD133⁺ cells were higher in familial PAH compared with idiopathic PAH and the control subjects; interestingly, in non-affected family members, the CD34⁺CD133⁺ cell counts were comparable to

that observed in Familial PAH group^[101]. Furthermore, patients with PAH and myelofibrosis have blood vessels morphologically similar to what is observed in myeloproliferative myelofibrosis such as, microvascular density, distended lumina and irregular branching. In addition, VEGF levels are much higher in patients with primary myelofibrosis compared with the controls; and even higher in patients with primary myelofibrosis associated with PH. However, in PH associated with myeloproliferative diseases, the levels of circulating endothelial progenitor cells and the bone marrow pericytes were lower^[103,104]. Almost a century ago it was thought that EC and hematopoietic cells have a common progenitor, hemangioblasts. Furthermore, EC and hematopoietic cells affect each other^[105], which may explain the increased incidence of PH in CMPD and myelofibrosis accompanying PH. Transplantation of bone marrow-derived CD133⁺ cells from PAH patients into mice has been shown to result in endothelial injury, angioproliferative remodeling of pulmonary vasculature and right ventricular failure; CD133⁺ cells from control subjects, however, had no effect^[106]. Recent studies have shown that bone marrow cells from BMPR2 mutant mice when transplanted into control mice induce PH, whereas bone marrow cells from the control mice protect mutant mice from developing PH^[107]. These results further support a causal relationship between vascular and hematopoietic systems.

Autoimmunity, PH and hematological disorders

Autoimmunity is a well-known underlying feature of hematological disorders as well as of PH. Autoimmune diseases such as systemic sclerosis, systemic lupus erythematosus (SLE), Sjogren's disease, and mixed connective tissue diseases are known to be associated with PH^[108-110]. Loss of CD4⁺CD25⁺ cells, the T regulatory (Treg) cell population has been reported in several forms of PAH^[110]. Furthermore, normal Treg function has been shown to limit the vascular injury and provide protection from developing PH^[111]. In 132 patients with SLE, the incidence of PH was 12.9%. PH patients had longer duration of anemia; oxygen delivery was inversely related to PA pressure, indicating that tissue hypoxia may play a greater role in the lupus-associated PH^[112]. Another patient with SLE and associated lupus anticoagulant and clotting disorder was described to have PH^[113].

Autoimmunity is also important in thyroid diseases and thyroid disease-associated PH. Scicchitano *et al.*^[114] in a recent review article have discussed the prevalence of PH in hypothyroid state as well in hyperthyroid state. Interestingly, approximately half of the patients with PAH have been shown to have autoimmune thyroid disease^[115]. Coagulation abnormalities associated with thyroiditis^[116] may lead to chronic embolism and eventually CTEPH. Furthermore, thyroid hormone participates in EC proliferation and facilitates angiogenesis. Recent studies with an angio-proliferative model (Sugen + hypoxia) of PH have shown that

thyroidectomy inhibits angioproliferation and reduces the expression of p-ERK1/2, integrin receptor $\alpha_v\beta_3$, fibroblast growth factor (FGF) 2 and FGF receptor^[117]. These results suggest that the status of thyroid function in PH is important and it may affect the progression of the disease adversely.

Evan's syndrome includes immune thrombocytopenia and associated autoimmune hemolytic anemia. Connor *et al.*^[118] reported 2 children with Evan's syndrome and associated PH; both with the evidence of perivascular lymphoid infiltration indicative of vasculitis. Both improved with steroid and rituximab treatment. The incidence of PH in Evans's syndrome, however, is not known. PH has also been reported in an adult patient with autoimmune hemolytic anemia who improved significantly on regular steroid therapy^[119].

Therapy-associated PH

A number of alkylating agents including cyclophosphamide, bleomycin, mitomycin used for hematological diseases have been shown to lead to PVOD and PH^[11,120]. Other therapeutic measures used for hematological disorders such as tyrosine kinase inhibitor dasatinib, interferon, splenectomy, bone marrow transplantation (BMT) and radiation also contribute to PH as discussed below.

Dasatinib: CML is caused by active BCR/ABL tyrosine kinase. Tyrosine kinase inhibitor, imatinib inhibits BCR/ABL and platelet-derived growth factor (PDGF), and has been used as a first line treatment for CML with good results. However about 29% of patients do not recover completely with imatinib, therefore, newer tyrosine kinase inhibitor, dasatinib is used as a second line treatment. Dasatinib inhibits Src kinase in addition to BCR/ABL and PDGF. Several case reports have appeared showing the development of precapillary PH after about 8-48 mo of dasatinib therapy^[121-127]. In the French experience, the incidence of dasatinib-associated PH is 0.45%. The patients, however, did not recover fully after having been taken off dasatinib treatment. Interestingly, in the monocrotaline (MCT) and hypoxia-induced PH models, the pretreatment with dasatinib, unlike imatinib induced increased pulmonary artery pressure and increased inflammatory cells in the perivascular area. Furthermore, *in vitro* studies with human pulmonary EC, dasatinib induced apoptosis in a dose dependent manner through mitochondrial reactive oxygen species generation^[128,129]. Interestingly a number of patients with dasatinib-induced PH is accompanied by pleural effusion (as high as 68%), which is not observed in classical PH. In most cases, discontinuing the medication appeared to have reversed PH; however, in a few cases prolonged PH therapy might be required^[130]. Recent studies have shown that the inhibition of Src tyrosine kinase or dasatinib increases pulmonary artery pressure, and depolarizes PA SMC by altering potassium channels^[131]. Thus, dasatinib-associated Src inhibition and the alterations in potassium channels may be

responsible for the increased vasoconstriction and PH. It is noteworthy that decreased expression of Src tyrosine kinase has been reported in the lungs of patients with PAH^[132]. It is suggested that Src function may depend on the state of vascular SMC^[133].

Interferon: Interferon (IFN) α and β are used for various hematological disorders, cancer and infection especially hepatitis C. Evidence is accumulating to suggest that IFN pathway may have a role in the pathobiology of PH. INF therapy has been shown to be complicated by vasculopathy. IFN therapy has been shown to lead to reversible PH and in some cases irreversible PH^[134-136]. Infusion of IFN- α into sheep has been shown to elevate pulmonary artery pressure associated with increased expression of thromboxane B₂, a stable byproduct of thromboxane A₂, a vasoconstrictor; that is attenuated by a selective thromboxane A₂ synthetase inhibitor, OKY-046^[137]. Interestingly, a subgroup of patients treated with INF exhibit increased levels of endothelin-1 (ET-1), which is known to play an important role in PH. Recent studies have shown that IFN induces *ET1* gene and IFN-inducible protein IP10, a mediator of inflammation in vascular SMC; and the combination of IFN and TNF- α produce the highest amount of ET1. These cytokines have direct effect on ET1 transcription and also on increased translocation of NF- κ B and STAT1^[138]. Importantly, recent studies have shown increased levels of IP10 and ET1 in patients with PAH which correlated positively with serum brain natriuretic peptide and the status of the disease. These Authors have further shown increased type 1 IFN receptor (IFNR1) protein levels in the lungs of patients with PAH compared with the controls. Furthermore, IFNR1 knockout mice exhibit attenuated response to hypoxia^[139]. These studies strongly indicate a role for IFN in the pathobiology of PAH.

Splenectomy: A number of patients who undergo splenectomy following trauma or for various hematological disorders develop PH, associated with histological changes in pulmonary arteries such as intimal fibrosis, plexiform lesions and thrombo-embolic lesions. The prevalence of PH in patients in the presence of asplenia is reported to be 11.5%^[140]. In another study, 22 out of 257 patients with CTEPH (8.6%) had a prior history of splenectomy, compared with the positive history of splenectomy in 2.5% of idiopathic PAH patients and 0.4% in general population^[77]. PH has been shown to occur several years after splenectomy for hereditary spherocytosis^[74,75], stomatocytosis^[78], thalassemia^[141] and Hb Mainz hemolytic anemia^[142]. Splenectomy is associated with deep vein thrombosis and un-resolving recurrent thrombosis eventually leading to CTEPH. Loss of spleen results in a loss of filtering function leading to abnormal circulating erythrocytes and the activation of coagulation. The activation of platelets

enhances thrombin generation as well as cytokine activation. Human thrombi obtained after pulmonary endarterectomy revealed increased platelet-derived micro-particles and increased anionic phospholipids (phosphatidylserine, phosphatidylethanol and phosphatidylglycerine), reduced angiogenesis related gene expression, and reduced vascular canalization. These micro-particles are pro-coagulant. In addition, in a murine model of CTEPH, inhibition of angiogenesis was associated with delay in thrombus resolution^[143,144]. In a rabbit model with splenic artery ligation, transfusion of sonicated blood resulted in platelet rich thrombi in pulmonary circulation; in contrast, transfusion of normal blood did not have any effect^[145].

BMT: BMT is used for a number of blood disorders and cancer. Hepatic veno-occlusive disease is a well-established complication of BMT and cytotoxic drugs. In 1984, Troussard *et al*^[146] were the first ones to report a child who developed PVOD a few years after having received BMT for a relapse of acute lymphoblastic leukemia. Since then, PVOD following BMT have been reported in several adults and children^[147-152]. Hepatic veno-occlusive disease is a recognized complication of cytotoxic therapy used concomitantly with BMT. BMT in combination with cytotoxic drugs and radiation increases the chances of EC damage and PH. Another possibility that has been considered is that malignancy itself may cause PH^[151]. Transplantation-associated thrombotic microangiopathy (TM-TMA), a known complication of BMT is caused by EC injury resulting in thrombin and fibrin deposition in microcirculation with ensuing organ damage. Jodele *et al*^[153] have described 5 children who developed severe PH 71-205 d after having undergone hemopoietic stem cell transplantation. These children did have TM-TMA 56-101 d before the diagnosis of PH was made. PH can occur from a few months to several years after transplantation. In addition, PH without any evidence of PVOD was reported to occur in an adult almost a year after BMT^[154]. A 5.25-year-old child underwent BMT after conditioning with cyclophosphamide and antithymocyte globulin; and he was treated with cyclosporine A and a short course of methotrexate to prevent graft-*vs*-host disease. Within a month of BMT, he developed respiratory distress, anemia and thrombocytopenia. Approximately 1.5 mo later, he was diagnosed to have microangiopathic changes. His condition, however, stabilized after cyclosporine A was discontinued and treatment with mycophenolate mofetil was started. About a year or so later he started to have vague respiratory symptoms which was subsequently diagnosed as severe PH^[155]. These cases illustrate that PH can occur early or late after BMT. Cytotoxic drugs and radiation used to prepare the patient for BMT and to prevent graft-*vs*-host disease can contribute to EC damage leading to pulmonary vasculopathy. These patients need to be carefully monitored and PH should be considered a possibility when they present with

pulmonary symptoms.

Radiation injury: Lung radiation leads to pneumonitis, fibrosis and vascular injury. Thoracic or whole body radiation is used for several types of lung cancer; and at times radiation in combination with immunosuppressive drugs is used before BMT. PVOD and pulmonary insufficiency have been reported to occur several months to years following therapy for cancer that included chemotherapy and radiation therapy. Histopathological changes in the lungs comprised interstitial fibrosis, thromboemboli, veno-occlusive lesions, and medial hypertrophy of pulmonary arteries, consistent with PVOD^[156,157]. In addition, a 14-year-old was reported to have developed PH after receiving radiation therapy during infancy following the surgical removal of neuroblastoma arising from the left of the thoracic spine. At cardiac catheterization significant PH was noted. In addition, the branches of left pulmonary artery were described as hypoplastic, and the pulmonary veins from the left lung were underdeveloped^[158].

EC play a pivotal role in radiation-induced vascular injury. Irradiated EC from rectal adenocarcinoma have been shown to induce fibrogenic phenotype in vascular SMC, and increase proliferation and migration^[159]. Furthermore, several experimental studies have shown radiation injury resulting in elevated pulmonary artery pressure, and structural remodeling of the small pulmonary arteries. In a sheep model, several weeks after the whole lung exposure to radiation resulted in abnormal vascular reactivity, PH and pulmonary vascular remodeling^[160]. In a mouse model, low dose radiation resulted in EC injury, followed by rapid recovery. However, a higher dose resulted not only in EC injury, but also a delay in recovery followed by prolonged EC proliferation, fibroblast proliferation and collagen secretion indicative of significant vascular damage^[161]. In a rat model, radiation injury induced pulmonary vascular EC damage followed by medial wall and adventitial thickening, neointima formation and obliteration of vessels similar to what is observed in PAH^[162].

These studies underscore the fact that vascular EC are susceptible to radiation injury. The patients who receive radiation therapy with or without alkylating drugs are at a risk of developing PH. PH has been shown to occur several years after the cessation of therapy; therefore these patients need a long careful follow-up.

IRON HOMEOSTASIS AND PAH

Deregulation of iron homeostasis and resulting alterations in iron availability plays an important role in the pathogenesis of cardiovascular diseases including PH. Both iron deficiency and iron overload have deleterious effect on cardiovascular system. Iron deficiency has been shown to have an adverse effect on survival in patients with chronic heart failure^[163]. Anemia in PH is

associated with worse function and poor survival^[164]. Iron deficiency is being recognized as an important factor in the prognosis of PAH. Low transferrin saturation, an indicator of iron deficiency has been reported in PAH patients, particularly the ones with BMPR2 mutation, but not in the CTEPH group. In this group of PAH patients, 72% of iron deficient patients had anemia, whereas only 4% in non-iron deficient patients^[20]. In another study, iron deficiency was found in 43% of 70 patients with idiopathic PAH accompanied by low exercise capacity. However, anemia did not affect the exercise intolerance. Interestingly, 8 out of 18 patients did not respond to oral iron therapy^[165]. Red cell distribution width (RDW), a biomarker of anemia has a better survival predictive value independent of NT-proBNP levels and 6 min walk distance. Increased RDW was accompanied by other indicators of iron deficiency such as decreased ferritin levels and low transferrin saturation. Patients with increased soluble TfR (sTfR) had higher mortality independent of WHO class or exercise capacity. sTfR levels are a sensitive marker of tissue iron availability, unaffected by inflammation. Interestingly, hepcidin levels were increased in PAH despite iron deficiency. Hepcidin which restricts iron absorption is stimulated by cytokines and BMP6; however, hepcidin levels did not correlate with IL-6 levels. Since a number of patients have BMPR2 mutation and loss of function, it is likely that increased BMP6 levels secondary to BMPR2 loss may increase hepcidin levels. Furthermore, erythropoietin levels are increased in idiopathic PAH despite the fact that these patients were not anemic. The hematocrit and Hb levels were not different compared with the controls. Erythropoietin is known to reduce hepcidin levels in order to increase iron uptake. Increased levels of hepcidin in the presence of increased erythropoietin indicates deregulated erythropoiesis in idiopathic PAH^[166,167]. In 29 patients with idiopathic PAH, 46.2% of iron deficient patients belonged to NYHA functional class 3 or higher compared with 12.5% in non-iron deficient. There were no differences in the hematocrit or Hb levels between the two groups. The iron deficiency was related to the severity^[168]. In addition, zinc protoporphyrin (ZnPP) levels, indicative of iron deficiency was significantly higher in patients with idiopathic PAH associated with increased RDW; however, ZnPP levels were not altered in "Associated" PAH. Iron containing protein is also required for mitochondrial electron transport and catalyzes reactions that form NO^[169]. Intravenous iron therapy in patients with idiopathic PAH was well tolerated and it improved endurance capacity; however, it did not alter cardiac function^[170]. Thus, iron deficiency seems to be a more important prognosticator compared with anemia.

Iron deficiency is common in patients with systemic sclerosis (SSc) associated with PH than in the non-PH group. PH was present in 27.8% of patients with SSc. Iron deficiency was associated with poor exercise tolerance and survival. Hepcidin levels were high in the SSc population, but did not correlate with IL-6

levels. Hb levels, however, were not altered. Soluble transferrin receptor (sTfR) levels in both groups were significantly increased associated with iron deficiency^[171]. Interestingly, iron-depletion by desferrioxamine infusion in normal individuals resulted in higher systolic pulmonary artery pressure during 8 h hypoxia compared with the iron-repleted individuals. Thus, the alterations in iron availability affect the pulmonary vascular response to hypoxia. HIF is implicated in hypoxia; it is likely that increased iron potentiates HIF hydroxylation and its degradation^[172]. Sufficient iron availability is required for adjustment to high-altitude hypoxia. There is a close connection between oxygen and iron homeostasis^[173].

Recently it was reported that iron-deficient diet in rats resulted in elevated PA pressure, right ventricular hypertrophy, vascular remodeling, and increased expression of HIF1 α , HIF2 α , STAT3 activation and aerobic glycolysis, which could be reversed by iron therapy^[174]. Furthermore, deletion of iron regulatory protein 1 (IRP1) in mice leads to PH and polycythemia that is exacerbated by low iron diet, resulting in increased HIF2 α levels and ET1 in EC. Iron deficiency can stabilize HIF2 α by diminishing activity of iron-dependent prolyl hydroxylases involved in HIF2 α degradation^[175]. In contrast, dietary iron restriction attenuated monocrotaline-induced PH, although, the serum iron concentration in MCT group was not different from the control group. However, the expression of TfR1 in pulmonary arteries was increased. Interestingly, TfR1 hetero-knockout mice showed attenuated hypoxia-induced PH, right ventricular hypertrophy and vascular remodeling^[176,177]. Iron chelation has been shown to attenuate hypoxia-induced PH, pulmonary vascular remodeling and right ventricular hypertrophy in rats. In addition, carbonylation of proteins was increased in hypoxia-induced rats as well in the plasma of the patients with PAH indicative of oxidative stress^[178]. Furthermore, PH in patients with idiopathic pulmonary fibrosis was shown to correlate with iron deposition in alveolar spaces^[179]. These foregoing results show opposite effects of iron levels on pulmonary vasculature. Iron homeostasis is intricately balanced and maintained; any injury and/or stress can alter this balance resulting in iron overload or iron deficiency. Mitochondria play a pivotal role in energy and iron metabolism^[180]. The opposing effects of iron levels observed in different forms of PH may depend on the level of non-transferrin-bound iron and on the status/health of mitochondria.

In summary, hemopoietin system, pulmonary vasculature and iron metabolism are intricately related. Hematological disorders affect pulmonary vasculature and PH can cause myelofibrosis. Deregulated iron homeostasis and resulting status and function of mitochondria in PH may have an important effect on prognosis.

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