Angiopoietin-1 and Pulmonary Hypertension
Cause or Cure?
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Our very existence depends on the air that we breathe, as well as the remarkable systems that have evolved to ensure that the oxygen we take into our lungs is efficiently delivered to the rest of the body via the bloodstream. When these systems begin to fail, life itself can become quite tenuous. Such failure occurs in pulmonary hypertension, a rare but serious disease whose pathophysiology remains obscure and increasingly controversial, as highlighted by two recent studies. Both studies focus on the potential role of angiopoietin-1 in this disease, but reach entirely antithetical conclusions.

The right side of the heart pumps blood into the lung vasculature, which consists of a low-resistance network that normally adjusts to increases in blood flow (eg, as necessitated by exercise) by dilation of its terminal arterioles to allow for increased flow without increasing resistance. In pulmonary hypertension, pulmonary arterial pressure is increased at rest and ratchets up dramatically with exercise, due to an inability to easily accommodate increased flow, imposing stress on the right ventricle. In response to the increased back pressure, the right side of the heart can hypertrophy to the point of failure. Current treatments are moderately effective at best. A study featured in this issue of Circulation Research, from the laboratory of Duncan Stewart, claims that angiopoietin-1 can have dramatic protective effects in an animal model of pulmonary hypertension. On the other hand, a recent article in the New England Journal of Medicine by Thistlethwaite and colleagues argues quite the opposite, based on examining angiopoietin-1 levels and activities in human patients, and instead suggests that angiopoietin-1 might be to blame for causing this disease. Why the two opposing perspectives? Evaluating the controversy requires some background on angiopoietin-1, as well as some insight into different views of what might be the cellular basis of this poorly understood disease.

The number of growth factors that specifically act on the blood vasculature is quite small and are limited to two families of factors known by their prototypical members—the vascular endothelial growth factor (VEGF) family and the angiopoietins. Members of these families achieve their specificity based on the limited distributions of their receptors, which are expressed almost exclusively on the vascular endothelium. Both families act primarily via receptor tyrosine kinases, with those for the VEGFs termed VEGFR1, VEGFR2, and VEGFR3, and those for the angiopoietins termed Tie1 and Tie2. The enormous interest in these two families of growth factors results from the realization that they evolved to play very specific and critical roles in the vasculature, as initially suggested by their receptor distributions, and more recently confirmed by genetic knockout of these factors and their receptors. While VEGF was discovered more than two decades ago, angiopoietin-1 has been identified much more recently, and thus its biological, pathological, and potential therapeutic roles are less well understood. One major emerging theme is that the VEGFs and the angiopoietins are not redundant, but instead play distinct and complementary roles, with the VEGFs acting early to initiate vessel growth, and the angiopoietins acting subsequently to promote vessel maturation and maintenance. Thus, while genetic ablation of VEGF-A causes embryonic lethality by preventing initial vessel outgrowth, knockout of angiopoietin-1 allows for initial vascular network formation, but these primitive vessels fail to mature, do not properly incorporate supporting smooth muscle cells, and begin to regress. A vessel maintenance or survival role for angiopoietin-1 has been supported by in vitro studies, which show that, although angiopoietin-1 differs from VEGF-A in that it cannot promote endothelial cell proliferation, it can inferred more than two decades ago, angiopoietin-1 has been identified much more recently, and thus its biological, pathological, and potential therapeutic roles are less well understood. One major emerging theme is that the VEGFs and the angiopoietins are not redundant, but instead play distinct and complementary roles, with the VEGFs acting early to initiate vessel growth, and the angiopoietins acting subsequently to promote vessel maturation and maintenance. Thus, while genetic ablation of VEGF-A causes embryonic lethality by preventing initial vessel outgrowth, knockout of angiopoietin-1 allows for initial vascular network formation, but these primitive vessels fail to mature, do not properly incorporate supporting smooth muscle cells, and begin to regress. A vessel maintenance or survival role for angiopoietin-1 has been supported by in vitro studies, which show that, although angiopoietin-1 differs from VEGF-A in that it cannot promote endothelial cell proliferation, it can
increased pulmonary vascular resistance (Figure, see model 1). Supporting this view is the link between rare familial cases of pulmonary hypertension and mutations in bone morphogenetic receptor type 2 (BMPR2)\textsuperscript{16,17} which, despite its name, is thought to also regulate smooth muscle proliferation and differentiation. The question asked by the Thistlethwaite group is whether angiopoietin-1 might somehow provide a link into the BMP pathway for the more common sporadic forms of pulmonary hypertension, whose causes are unknown but thought to result from hypoxia, left-sided heart failure, use of anorexigenic drugs, and other toxic challenges. Their rationale was that since angiopoietin-1 seems to normally play a role in the developing vessel wall (it is made by smooth muscle cells and acts on the endothelium), it might be aberrantly involved in a disease with excessive smooth muscle proliferation. Consistent with this possibility, the Thistlethwaite group reports\textsuperscript{1} that angiopoietin-1 and associated activation of its Tie2 receptor cannot be detected in normal human lung samples, but are highly elevated in lung samples from patients suffering from pulmonary hypertension. Moreover, they find an associated decrease not in BMPR2, but in BMPR1A, and further show that angiopoietin-1 can repress BMPR1A levels when added to cultures of pulmonary arterial endothelial cells. These results lead them to conclude that excess angiopoietin-1 plays a causative role in sporadic pulmonary hypertension by promoting smooth muscle hyperplasia (Figure, see model 1), specifically by linking it to downregulation of the BMP pathway that has already been implicated in familial pulmonary hypertension. Further support for this conclusion comes from their own unpublished claims that administration of angiopoietin-1 to rodents induces clinical and pathologic pulmonary hypertension, including the smooth muscle hyperplasia characteristic of the human disease.

The Stewart group begins with a very different rationale and comes to a very different conclusion.\textsuperscript{2} They focus on the possibility that pulmonary hypertension may be due to endothelial cell dysfunction. They start with the notion that this could involve a disturbance in endothelial vasodilator/vasoconstrictor balance, but they end with the possibility that endothelial cell apoptosis may lead to vessel loss that decreases the pulmonary vascular bed, leading to increased resistance (Figure, see model 2). They exploit one of the most intensively studied animal models of pulmonary hypertension, in which rats are treated with monocrotaline (MCT), and show that such treatment not only causes pulmonary hypertension (with associated increases in right ventricular pressure and size) and profound mortality but is associated with reduction in endothelial NO synthase mRNA and endothelial cell apoptosis in the microvasculature, particularly in the critically positioned terminal arterioles. Administration of angiopoietin-1 into this model, using a novel cell-based delivery system designed to provide angiopoietin-1 to these key sites, dramatically prevents mortality, improves all measures of pulmonary hemodynamics, and rescues endothelial cells from apoptosis (Figure, see model 2).

So which rationale, and which set of conclusions, are most relevant for patients suffering from pulmonary hypertension? Thistlethwaite would argue that angiopoietin-1 (or Tie2) blockers should be administered to such patients, while Stewart would instead administer angiopoietin-1 itself. In support of Thistlethwaite’s perspective, her conclusions were mostly drawn from the analysis of human samples, in contrast to those of Stewart and colleagues, which were based exclusively on a toxin-generated animal model with unknown relevance to the human disease. However, some of the observations of the Thistlethwaite group run counter to previous findings. For example, it has previously been shown that angiopoietin-1 and activated Tie2 levels are normally highest in the lung (eg,\textsuperscript{18}), making it difficult to understand why the Thistlethwaite group could only detect angiopoietin-1 and activated Tie2 levels in lung samples from pulmonary hypertension patients. In addition, in multiple settings in which angiopoietin-1 has been administered to rodents,\textsuperscript{13-15,19} smooth muscle hyperplasia was not noted in the vascular beds examined. Furthermore, even in human venous malformations in which Tie2 appears to be activated by genetic mutation, resulting vascular lesions actually exhibit decreased smooth muscle coverage.\textsuperscript{20} Altogether, these previous findings seem to argue that while angiopoietin-1 and Tie2 may be required for normal endothelial-smooth muscle interactions, excess activation of this pathway need not lead to smooth muscle hyperplasia. It cannot be ruled out, of course, that such hyperplasia only occurs in particular vascular beds, or only after particular toxic challenges in these beds. It should also be noted that it is possible that the Thistlethwaite observation of increased angiopoietin-1 in pulmonary hypertension is correct, but that this increase reflects an insufficient compensatory response rather than a
cause, thus reconciling these observations with those of the Stewart group.

Stewart’s perspective seems more consistent with previous findings that the angiopoietin-1/Tie2 system promotes endothelial survival and maintenance, and this perspective is also strengthened by the fact that it is derived from manipulative (as opposed to circumstantial) studies in which administered angiopoietin-1 is shown to be rather dramatically protective in an animal model. It is also intriguing that the vessels that might be most at risk in pulmonary hypertension, ie, the terminal pulmonary arterioles, are known to normally have the barest of smooth muscle coatings, which could make them more susceptible to toxic challenges and thus most likely to benefit from a survival factor such as angiopoietin-1. Unfortunately, the findings of the Stewart group fall short in that it is hard to know how relevant their model is with respect to the human disease. One could easily argue that MCT does indeed cause pulmonary hypertension by causing endothelial apoptosis, and that angiopoietin-1 can effectively protect against MCT damage by preventing endothelial death, but that this model may not reproduce all of the features of the human disease. Thus, it is uncertain whether angiopoietin-1 would be protective or beneficial to patients suffering from pulmonary hypertension.

So, is angiopoietin-1 cause or cure for this terrible disease? It seems as if more data are required, and the current controversy will certainly fuel more intense efforts to evaluate the angiopoietin-1/Tie2 pathway in additional models of pulmonary hypertension.

References

Key Words: pulmonary hypertension □ angiopoietin-1 □ Tie2 □ vascular endothelial growth factor □ smooth muscle cells
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Circ Res. 2003;92:947-949
doi: 10.1161/01.RES.0000074031.94558.99

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