The monocrotaline model of pulmonary hypertension in perspective

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Gomez-Arroyo JG, Farkas L, Alhussaini AA, Farkas D, Kraskauskas D, Voelkel NF, Bogaard HJ. The monocrotaline model of pulmonary hypertension in perspective. Am J Physiol Lung Cell Mol Physiol 302: L363–L369, 2012. First published September 30, 2011; doi:10.1152/ajplung.00212.2011.—Severe forms of pulmonary arterial hypertension (PAH) are characterized by various degrees of remodeling of the pulmonary arterial vessels, which increases the pulmonary vascular resistance and right ventricular afterload, thus contributing to the development of right ventricle dysfunction and failure. Recent years have seen advances in the understanding of the pathobiology of PAH; however, many important questions remain unanswered. Elucidating the pathobiology of PAH continues to be critical to design new effective therapeutic strategies, and appropriate animal models of PAH are necessary to achieve the task. Although the monocrotaline rat model of PAH has contributed to a better understanding of vascular remodeling in pulmonary hypertension, we question the validity of this model as a preclinically relevant model of severe plexogenic PAH. Here we review pertinent publications that either have been forgotten or ignored, and we reexamine the monocrotaline model in the context of human forms of PAH.

Investigations of the pathobiology of PH have recently shifted from the early concepts of pressure and flow, to the state-of-the art concepts of cell-to-cell interactions (45), apoptosis resistance (64), and quasi-malignancy (59). Yet, many questions remain unanswered, and, despite the development of new pharmacotherapies, treatments for PAH are still limited and PAH-related mortality remains unacceptably high (5). Elucidating the pathobiology of PAH continues to be critical for the design of new effective therapeutic strategies, and animal models are fundamental to achieve this objective. In this context, it is reasonable to interrogate experimental models presently in use to address which aspects of each model reproduce the salient features of the human disease. Although the MCT rat model has contributed to a better understanding of vascular remodeling in PH, we question whether this model remains productive as a preclinically relevant model of severe plexogenic PAH. Based on an extensive review of the literature and our own data, we wish to put this PH model in a greater perspective.

Monocrotaline Pyrrole Toxicity and the “MCT Syndrome”

MCT is an 11-membered macrocyclic pyrrolizidine alkaloid (PA) derived from the seeds of the Crotalaria spectabilis plant (Fig. 1, A and B). The MCT alkaloid is activated to the reactive pyrrolo metabolite dehydromonocrotaline (MCTP) in the liver, a reaction that is highly dependent on cytochrome P-450 (CYP3A4) (61, 84). Specific metabolic inducers of this cytochrome increase the MCTP production by the rat liver, whereas specific anti-CYP3A4 antibodies inhibit it (31, 61). When ingested, MCT induces a syndrome (Table 1) characterized, among other manifestations, by PH, pulmonary mononuclear vasculitis (acute necrotizing pulmonary arteries in about one-third of the animals), and RV hypertrophy (32, 36).

Although it has been reported that MCT injures pulmonary endothelial cells (32, 63), the exact toxicological mechanisms by which MCT initiates lung toxicity remain unclear. Lee et al. (38) have shown that pulmonary arterial endothelial cells (PAEC) exposed to MCT develop megalocytosis characterized by an enlarged Golgi apparatus, displacement of endothelial nitric oxide synthase, and decreased cell-surface/caveolar nitric oxide. MCT-treated endothelial cells demonstrate marked disruptions of intracellular membrane trafficking that affect several cell membrane proteins (68). Huang et al. (30) have reported that MCT-induced loss of membrane proteins results in the activation of proliferative and antiapoptotic factors, and deregulation of nitric oxide signaling, leading to lung vascular changes. The initial MCT-induced endothelial cell damage has also been linked to bone morphogenetic protein receptor II (BMPR II) dysfunction and BMP signaling disruption, as well as increased expression of intracellular elements involved in the sequestration and inhibition of the BMPR II activity (60).
Nakayama et al. (46) demonstrated that, in human PAEC, the monocrotaline pyrrole significantly induced the Nrf2-mediated stress response pathway and increased caspase-3 activation. Paradoxically, although there is vast evidence to suggest that MCT elicits PAEC dysfunction on multiple levels, the MCT PAH model is characterized predominantly by pulmonary arterial medial hypertrophy (Fig. 1D) but not by endothelial cell-mediated angioobliteration. In addition to the vascular changes, monocrotaline-treated rats exhibit marked perivascular edema (F, long arrow; arrowhead marks a normal septa), and megalocytosis of type I pneumocytes (H, long arrows; arrowhead marks a normal type I pneumocyte nucleus).

Table 1. The monocrotaline syndrome

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Dose Range, mg/kg</th>
<th>Ref. No.</th>
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<tbody>
<tr>
<td>Acute lung injury</td>
<td>60–100</td>
<td>20, 33, 62, 66, 74</td>
</tr>
<tr>
<td>Interstitial pulmonary fibrosis</td>
<td>2.4–100</td>
<td>29, 43, 44</td>
</tr>
<tr>
<td>Necrotizing pulmonary arteritis</td>
<td>Not quantified</td>
<td>32, 36, 84</td>
</tr>
<tr>
<td>Pulmonary hypertension</td>
<td>45–60</td>
<td>8, 32, 49, 56, 65, 66, 86, 87</td>
</tr>
<tr>
<td>RV hypertrophy</td>
<td>45–60</td>
<td>8, 10, 25, 32, 49, 56, 65, 66, 86, 87</td>
</tr>
<tr>
<td>Myocarditis</td>
<td>50–60</td>
<td>1, 10, 25</td>
</tr>
<tr>
<td>Hepatic venooclusive disease</td>
<td>60–300</td>
<td>13–17, 19, 21, 39, 40, 54, 83, 84</td>
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RV, right ventricle.
Hematopoietic megakaryocytosis (Fig. 1A) was significant alveolar septal thickening (Fig. 1B). Dumitrascu et al. (20) reported that the PaO2 measured in blood samples from MCT-treated mice was significantly lower compared with controls (65 ± 2 vs. 92 ± 9 mmHg). Similarly, Schermuly et al. (66) reported that MCT-treated rats exhibit a significantly decreased partial pressure of arterial oxygen/fraction of inspired oxygen ratio (PaO2/FIO2 of 300 vs. 378 mmHg in control rats), whereas Klein and Schäfer (33) reported an PaO2/FIO2 of 200 mmHg. A PaO2/FIO2 below 300 is considered part of the clinical criteria for the diagnosis of acute lung injury (ALI) (6).

Lai et al. (35) described the changes in ventilatory capacity following MCT administration in rats. The DLCO was decreased by 2–3 wk post-MCT injection, and this decrease was coincident with increased alveolar wall thickness. These findings suggest that the ventilatory changes and alterations on the level of gas exchange occur before the development of PH. Concurrent with the alterations in gas exchange, ALI is characterized by a massive inflammatory cell influx in the lungs (2). This accumulation is reflected by a neutrophil-rich bronchoalveolar lavage fluid (23). MCT-treated mice exhibit significantly higher levels of granulocytes in the bronchoalveolar lavage fluid compared with controls (88). In addition to the increased granulocyte transmigration into the alveolar space, lung microvascular leakage has been reported in MCT-injured rats (74), and this finding partially explains the marked pulmonary edema present in rat models of MCT-induced PH/lung injury (57, 62, 70). In the aggregate, the lung tissue abnormalities induced by MCT are consistent with a model of ALI.

### MCT-Induced Liver Toxicity: A Model for Venoocclusive Hepatic Disease

It is well known that PA can induce liver toxicity, and this has been a serious problem in third world countries (13, 14, 19). The most frequent outcome of PA toxicity, in either humans or animals, is hepatic injury (84). MCT induces damage of sinusoidal endothelial cells, central venular endothelial cells, and hepatic parenchymal cells (17, 39). These initial lesions give way to a subacute phase of fibrotic occlusion of central and sublobular veins and sinusoidal fibrosis (Fig. 2F), making MCT a suitable model for hepatic venoocclusive disease (15). In dogs, MCT induces hepatic venoocclusive disease, which is accompanied by an increase in splenic pressure (54), and a single dose of 60 mg/kg has been shown to induce significant portal hypertension in dogs (21). Whereas the MCT liver toxicity in rats appears to be triggered only by large doses of the monocrotaline pyrrole, in MCT PH studies, the potential contribution of liver disease, and perhaps portal hypertension, to the development of the pulmonary vascular disease has not been considered.

### MCT-Induced Myocarditis

MCT-treated rats develop significant PH and marked RV hypertrophy (Fig. 2A, also see Refs. 8, 32, 56, 65, and 75). Tradi-

**Table 2. Pulmonary vascular changes and pulmonary hypertension in monocrotaline-treated animals**

<table>
<thead>
<tr>
<th>Monocrotaline Dose, mg·kg⁻¹·dose⁻¹</th>
<th>RVSP</th>
<th>RV/LV + S</th>
<th>Other Observations</th>
<th>Ref. No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>Not reported</td>
<td>0.74 ± 0.08</td>
<td>Lung vessel leak, lipid-laden macrophages</td>
<td>74</td>
</tr>
<tr>
<td>60</td>
<td>79.2 ± 6.2</td>
<td>0.95 ± 0.05</td>
<td>Sustained ventricular tachycardias/ fibrillation</td>
<td>4</td>
</tr>
<tr>
<td>60</td>
<td>34.9 ± 2.1</td>
<td>0.52 ± 0.04</td>
<td></td>
<td>41</td>
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<tr>
<td>60</td>
<td>48 ± 3.5</td>
<td>0.72 ± 0.04</td>
<td>Significant RV function impairment. Worsening after exercise. Marked leukocyte infiltration to RV</td>
<td>25</td>
</tr>
<tr>
<td>40</td>
<td>36 ± 2.8</td>
<td>0.60 ± 0.05</td>
<td>Functional hypertrophy, improvement after exercise</td>
<td>25</td>
</tr>
<tr>
<td>50</td>
<td>51 ± 35.3</td>
<td>Not reported</td>
<td>No signs of right heart failure signs (dyspnea or peripheral edema, ascites) at the time of cardiac excision</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>30 ± 4**</td>
<td>Not reported</td>
<td>Dehydromonocrotaline was used in beagles</td>
<td>24</td>
</tr>
<tr>
<td>60</td>
<td>82.9 ± 6.0</td>
<td>0.51 ± 0.02</td>
<td></td>
<td>33</td>
</tr>
</tbody>
</table>

Data for right ventricular systolic pressure (RVSP) and right ventricle/left ventricle + septum (RV/LV + S) are means ± SD. **Mean pulmonary artery pressure.
tional concepts suggest that the RV dysfunction of MCT-treated rats is a direct consequence of pressure overload. Interestingly, despite having lower pulmonary artery pressure and a similar degree of RV dysfunction compared with the SU5416/hypoxia model (Fig. 2, B and C), MCT-treated rats exhibit a significantly higher mortality rate compared with the SU5416/hypoxia model (D). Rats treated with a dose of 160 mg/kg or higher develop liver alterations consistent with hepatic venoocclusive disease [E, reproduced with permission of Frank Snow (19)]. Histological analysis of MCT-treated right ventricles demonstrated a severe inflammatory infiltrate in the RV (F and G). A similar inflammatory infiltrate was present in the left ventricle of MCT-treated rats (H, arrows) and was associated with medial hypertrophy of coronary arterioles (H, arrowhead) and marked perivascular fibrosis (I). Immunohistochemistry reveals that the majority of the inflammatory infiltrates are prominently positive for the B cell marker CD20 (K), negative for CD68+ (J), and identifies few CD8+ cells (L). These results are consistent with an MCT-induced lymphocytic myocarditis. SuHx, SU5416/hypoxia-exposed rats; mPAP, mean pulmonary arterial pressure; RVID, right ventricular internal diameter.

Fig. 2. Both monocrotaline (MCT) and SU5416/hypoxia animals develop pulmonary hypertension, however, MCT-treated rats present with a lower degree of pulmonary hypertension compared with the SU5416/hypoxia model (A). Both models develop a similar degree of right ventricular (RV) dysfunction assessed by increased RV internal diameter (B) and decreased tricuspid annular planar systolic excursion (TAPSE, C), two heart rate-independent variables to evaluate RV function by echocardiogram. Although the pulmonary artery pressure is lower in MCT-treated rats, and RV dysfunction is similar in both models, MCT-treated rats exhibit a higher mortality rate compared with the SU5416/hypoxia model (D). Rats treated with a dose of 160 mg/kg or higher develop liver alterations consistent with hepatic venoocclusive disease [E, reproduced with permission of Frank Snow (19)]. Histological analysis of MCT-treated right ventricles demonstrated a severe inflammatory infiltrate in the RV (F and G). A similar inflammatory infiltrate was present in the left ventricle of MCT-treated rats (H, arrows) and was associated with medial hypertrophy of coronary arterioles (H, arrowhead) and marked perivascular fibrosis (I). Immunohistochemistry reveals that the majority of the inflammatory infiltrates are prominently positive for the B cell marker CD20 (K), negative for CD68+ (J), and identifies few CD8+ cells (L). These results are consistent with an MCT-induced lymphocytic myocarditis. SuHx, SU5416/hypoxia-exposed rats; mPAP, mean pulmonary arterial pressure; RVID, right ventricular internal diameter.
(Fig. 2, F and G). When characterized by immunohistochemistry, the majority of the leukocyte infiltrates were positive for CD20, a marker for B lymphocytes (Fig. 2K), whereas CD68 (a macrophage marker) was negative. CD8 (a cytotoxic T cell marker) was positive as well, but to a lesser extent. These results suggest perhaps that MCT induces a lymphocytic myocarditis. We also observed marked infiltration of inflammatory cells within the left ventricle associated with coronary arteriolar wall thickening (Fig. 2H) and marked perivascular fibrosis (Fig. 2F). The MCT-induced myocarditis may be responsible for significant left ventricular systolic dysfunction and impaired diastolic relaxation, also described by Akhavein et al. (1). Benoist and collaborators (4) have described a proarrhythmic substrate in the hearts of MCT-treated animals. Whether MCT-induced myocarditis or arrhythmias (4, 42) are the cause of death in rats, which can tolerate higher levels of RV afterload, remains undetermined but should be considered.

The role of a dysregulated immune system in the pathobiology of human PAH has become more apparent in recent years (28, 48, 80). Interestingly, only one single study has reported leukocyte infiltration in the right ventricles obtained from patients with idiopathic PAH (IPAH) and PAH associated with systemic sclerosis (SScPAH) (52). The authors reported a higher number of CD45+ and CD68+ cells in SScPAH compared with RV samples from IPAH patients. Whereas these histological findings make a case for a worse prognosis observed in patients with SScPAH, and could plausibly argue in favor of the MCT model, the number of CD45+ cells is far greater in the MCT-treated rats. Moreover, the authors investigating RV samples from PAH patients reported a significantly higher number of CD68+ cells while our results indicate that CD68+ cells are absent in the MCT-treated RV.

Of Mice and MCT

Because mice provide the opportunity of a vast spectrum of genetic manipulations, it is peculiar that a MCT mouse model of severe PAH has never been described. One (perhaps simplistic) hypothesis is that mice metabolize MCT differently from other species. Of the four members of the CYP3A family, CYP3A4 is of greatest importance in drug metabolism (18). Mice express CYP3A4 is of greatest importance in drug metabolism (18). Of the four members of the CYP3A family, CYP3A4 is of greatest importance in drug metabolism (18). Of Mice and MCT

REFERENCES


