The monocrotaline model of pulmonary hypertension in perspective

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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 pyrrole 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 antipapoptotic 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, blue line), alveolar septal thickening (G, 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>
</tr>
</thead>
<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. 1), significant alveolar septal thickening (Fig. 1).

Dumitrascu et al. (20) reported that the PaO2 measured in blood of MCT-injured rats develop angioblastic changes in the pulmonary vasculature resembling those of human disease or the SU5416/hypoxia rat model (82). However, plexiform-like vascular lesions have not been described after a “single hit” of MCT alone, while other pathological changes have been reported as a consequence of MCT exposure. MCT not only injures the pulmonary arteries but also induces alveolar edema, alveolar septal cell hyperplasia, and occlusion of pulmonary veins (20, 37). MCT-induced interstitial pulmonary fibrosis has also been described in mice (with variable doses and time points) (20, 29). Electron micrographs of MCT-treated animals revealed degeneration of both lung endothelial and type I epithelial cells, as well as marked interstitial hypercellularity and fibrosis (43, 44). Hayashi et al. (29) reported that a single dose of 100 mg/kg is sufficient to induce severe pulmonary fibrosis and/or interstitial pneumonia in mice, whereas other investigators have reported that pulmonary fibrosis seems to be only a late manifestation of MCT exposure (20). The monocrotiline pyrrole has also been described as an anti-mitotic agent (16, 55). In astrocytes, the monocrotiline pyrrole can induce DNA damage by generating DHP-derived DNA adducts, which induce DNA cross links, DNA-cellular protein conjugates, and apoptosis (46, 71, 81). MCT-induced DNA damage is reflected in persistent cell cycle arrest and is responsible for the cyto- and karyomegalgy (megalogalagy) described in pneumocytes, human pulmonary endothelial cells, glial cells, and hepatocytes of MCT-treated animals (38, 71, 83, 84). Particularly, type II pneumocytes seem to be highly affected by MCT-induced mitotic inhibition (85), which is partially mediated by altered polyamine metabolism (3). Confirming these previously reported data, compared with the SU5416/hypoxia model of angioblastic PH, the MCT-treated animals demonstrate marked perivascular edema (Fig. 1F), significant alveolar septal thickening (Fig. 1G), and type I pneumocyte megakariocytosis (Fig. 1H).

MCT-Induced Lung Toxicity: A Model of Acute Lung Injury

The vascular and parenchymal changes present in the MCT rat model seem to have a direct functional impact on gas exchange. 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 at 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.

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

<table>
<thead>
<tr>
<th>Monocrotiline 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>Significant RV function impairment. Worsening after exercise. Marked leukocyte infiltration to RV</td>
<td>25</td>
</tr>
<tr>
<td>60</td>
<td>48 ± 3.5</td>
<td>0.72 ± 0.04</td>
<td>Functional hypertrophy, improvement after exercise</td>
<td>25</td>
</tr>
<tr>
<td>40</td>
<td>36 ± 2.8</td>
<td>0.60 ± 0.05</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>50</td>
<td>51 ± 35.3</td>
<td>Not reported</td>
<td>Dehydromonocrotiline was used in beagles</td>
<td>24</td>
</tr>
<tr>
<td>40</td>
<td>30 ± 4**</td>
<td>Not reported</td>
<td>Significant RV function impairment. Worsening after exercise. Marked leukocyte infiltration to RV</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>82.9 ± 6.0</td>
<td>0.51 ± 0.02</td>
<td>Dehydromonocrotiline was used in beagles</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.

Okada et al. (51) originally described that, when used in combination with pneumectomy (a “second hit”), MCT-treated rats developed angioblastic changes in the pulmonary vasculature resembling those of human disease or the SU5416/hypoxia rat model (82). However, plexiform-like vascular lesions have not been described after a “single hit” of MCT alone, while other pathological changes have been reported as a consequence of MCT exposure. MCT not only injures the pulmonary arteries but also induces alveolar edema, alveolar septal cell hyperplasia, and occlusion of pulmonary veins (20, 37). MCT-induced interstitial pulmonary fibrosis has also been described in mice (20, 29). Electron micrographs of MCT-treated animals revealed degeneration of both lung endothelial and type I epithelial cells, as well as marked interstitial hypercellularity and fibrosis (43, 44). Hayashi et al. (29) reported that a single dose of 100 mg/kg is sufficient to induce severe pulmonary fibrosis and/or interstitial pneumonia in mice, whereas other investigators have reported that pulmonary fibrosis seems to be only a late manifestation of MCT exposure (20). The monocrotiline pyrrole has also been described as an anti-mitotic agent (16, 55). In astrocytes, the monocrotiline pyrrole can induce DNA damage by generating DHP-derived DNA adducts, which induce DNA cross links, DNA-cellular protein conjugates, and apoptosis (46, 71, 81). MCT-induced DNA damage is reflected in persistent cell cycle arrest and is responsible for the cyto- and karyomegalgy (megalogalagy) described in pneumocytes, human pulmonary endothelial cells, glial cells, and hepatocytes of MCT-treated animals (38, 71, 83, 84). Particularly, type II pneumocytes seem to be highly affected by MCT-induced mitotic inhibition (85), which is partially mediated by altered polyamine metabolism (3). Confirming these previously reported data, compared with the SU5416/hypoxia model of angioblastic PH, the MCT-treated animals demonstrate marked perivascular edema (Fig. 1F), significant alveolar septal thickening (Fig. 1G), and type I pneumocyte megakariocytosis (Fig. 1H).

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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. 2E), 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 monocrotiline 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). Tra-
tional concepts suggest that the RV dysfunction of MTC-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 of PH (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.

RV hypertrophy, MCT treatment has been associated with increased 67GaGalium uptake by scintigraphy (10) and marked neutrophil migration into the RV myocardium, even during early stages of the MCT syndrome (10). Whether this neutrophil infiltration was a consequence of RV pressure overload or consequence of a direct cardiac effect (perhaps microvascular endothelial cell damage) of MCT remains undetermined. Handoko et al. (25) have also demonstrated a widespread leukocyte infiltration of the right ventricle in MCT-treated rats. Our own data confirm the presence of multiple inflammatory cell foci throughout the RV
(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. 2I). 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 underdetermined but should be considered.

The role of a dysregulated immune system in the pathology 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 >100 putative CYP genes with functional impact on the CYP3A cluster (47), which make the metabolism of a drug by this cytochrome highly unpredictable (27). The question if CYP isoforms influence or modify the development of the MCT syndrome (Table 1) in mice has never been addressed mechanistically. However, researchers have tried to circumvent the problem of MCT metabolism by injecting ex vivo synthesized MCTP (20). Surprisingly, even MCTP (active MCT) was insufficient to reproduce a rat MCT syndrome in mice. In contrast, mice developed multiple signs of ALI in the first 7–10 days post-MCT injection, followed by resorption of lung edema by day 14–21, finally developing foci of lung fibrosis by day 28 (20). A possible explanation for this sequence of events in mice treated with MCTP is the fact that this compound is extremely unstable.

In conclusion, the MCT rat model of PH remains a model favored by many investigators. Here we reviewed pertinent publications that have either been forgotten, or ignored, and reexamined the MCT model in the pathobiological context of human forms of PAH. The MCT rat model continues to impact preclinical PAH research (73), and a significant amount of time and funding continues to be invested in testing new drugs in this model (78). We suggest that the MCT model may be informative in the context of inflammation and the role of lung injury and chronic inflammation in pulmonary vascular diseases. Pulmonary vasoconstriction seems to be an important mechanistic component of the MCT model (11, 41, 50, 67), and, while vasoconstriction occurs in a certain subpopulation of patients with PAH (those documenting a large vasoconstriction component), pulmonary interstitial edema, myocarditis, and hepatic venoocclusive disease [not to mention renal alterations (34)], which are part of the MCT syndrome, are certainly not associated with the human forms of severe PAH [renal insufficiency is, however, a late manifestation (69)]. It is true that (almost) all animal models are imperfect and that it matters which aspect, mechanism, or manifestation of disease a particular model can reproduce or investigate. Whereas the “two hits” model of MCT/pneumonectomy can reproduce the pertinent pulmonary vascular pathology of human PAH, the other mentioned components of the MCT syndrome may be confounding. In contrast to the SU5416/hypoxia model (75), a very large number of drugs and compounds have either prevented or improved PH in the MCT-alone (single-hit) model. Paradoxically, the animals, when untreated, die from undetermined causes. Hence the question: do MCT-treated rats die with PH or from PH? As a model of inflammation-associated PAH, the MCT-alone model may be informative but limited as a model of severe angioproliferative PAH, since the full syndrome associated with the development of PH (after a single injection of MCT) and the successful treatment of the MCT syndrome with practically any drug investigated (73) may have little in common with human forms of angio proliferative PAH.

DISCLOSURES

No conflicts of interest are declared by the authors.

REFERENCES


