Monocrotaline (MCT) is a pyrrole alkaloid that consistently causes pulmonary hypertension in rats (1). The mechanism of this form of pulmonary hypertension is unknown, but an initial acute injury phase characterized by morphological and functional evidence of endothelial cell damage occurs during the first week after administration (19). This is followed by an inflammatory phase characterized by the gradual development of pulmonary hypertension. Structural changes occur, including proliferation of medial smooth muscle in small pulmonary arteries (19), and pulmonary function abnormalities develop, including restriction and mild hypoxemia (8).

Miyauchi et al. (20) have recently implicated ET-1 in the pathogenesis of MCT-induced pulmonary hypertension. They demonstrated an increase in circulating ET-1 levels after MCT injection, although lung concentrations of both peptide and steady-state mRNA for ET-1 decreased. In addition, they showed that BQ-123 blunts MCT-induced pulmonary hypertension and pulmonary arterial medial thickening. However, responses to a specific ETA blocker could be misleading if ET-1 acting on the ETB receptor caused vasodilation, thereby blunting the development of pulmonary hypertension. In addition, the possible contribution of reduced cardiac output to the blunting of pulmonary hypertension during BQ-123 administration was not evaluated.

In the present study, we reasoned that blunting of MCT-induced pulmonary hypertension by simultaneous blockade of both ETA and ETB receptors would strengthen the evidence that ET-1 is involved in pathogenesis. We hypothesized that the nonspecific ET-receptor blocker bosentan (3, 4) would reduce pulmonary hypertension, pulmonary vascular remodeling, and right ventricular (RV) hypertrophy in MCT-injected rats. We also sought to determine whether bosentan inhibits pulmonary hypertension without af-

ENDOTHELIN (ET) is a potent vasoactive and mitogenic peptide that is synthesized and released by endothelial cells (30). It exists in three isoforms, ET-1, ET-2, and ET-3, with ET-1 appearing to be the most important in vascular regulation (16). ET-1 constricts pulmonary arteries under resting conditions but may have vasodilator actions when administered to preconstricted arteries (9). These opposing effects have been ascribed to the different actions of the ET receptors, of which two have been described: the endothelin A (ETA) receptor, which mediates vasoconstrictor and mitogenic actions (15), and the endothelin B (ETB) receptor. The ETB receptor has two subtypes: ETB1, which mediates vasodilation, at least partially via release of nitric oxide and prostacyclin (5), and ETB2, which mediates vasoconstrictor actions (5, 29).

These properties have led investigators to posit that ET-1 contributes to the pathogenesis of experimental and clinical forms of pulmonary hypertension. In chronic hypoxic pulmonary hypertension in rats, lung homogenerate concentrations and steady-state mRNA levels for ET-1 increase (6). In addition, blockade of ET activity by using either the specific ETA-receptor blocker cyclo-(D-Trp-D-Asp-Pro-D-Val-Leu) (BQ-123) or the nonspecific ET-1-receptor blocker bosentan prevents the development of both acute (2, 23) and chronic forms of hypoxic pulmonary hypertension (2). ET-1 has also been implicated in the Fawn-hooded rat model of idiopathic pulmonary hypertension (26). These rats have elevated lung tissue ET-1 levels, and vascular smooth muscle cells cultured from their pulmonary arteries have enhanced proliferative responses to ET-1 (26). Furthermore, humans with primary pulmonary hypertension have increased plasma ET-1 levels (27) as well as increased gene expression and immunoreactivity for ET-1 in perivascular lung tissue (7), suggesting a possible pathogenic role.
ffecting cardiac output. Finally, we examined the effect of administering bosentan early as opposed to late after MCT administration to assess relative contributions of ET-1 to the acute and later inflammatory phases. Because bosentan is an oral agent suitable for once-a-day administration, demonstrated efficacy in experimental models of pulmonary hypertension may have important clinical implications.

METHODS

Animals and materials. Male Sprague-Dawley rats (250–300 g) were obtained from Harlan Sprague Dawley Laboratories (Madison, WI). Bosentan [Ro 47–0203; 4-tert-butyl-N-[6-(2-hydroxy-ethoxy)-5-(2-methoxy-phenoxy)-2,2'-bipyrimidin-4-yl]-benzene sulfonamide] was a gift of M. Clozel, Hoffmann-LaRoche (Basel, Switzerland). MCT was obtained from Transworld Chemical (Rockville, MD). Big ET-1 was purchased from Peptides International (Louisville, KY). All other reagents were obtained from Sigma Chemical (St. Louis, MO) unless otherwise indicated.

Experimental design. A preliminary series of experiments determined the efficacy of bosentan in blocking the constrictor actions of big ET-1 and acute hypoxic pulmonary vasoconstriction in intact rats. Bosentan was dispersed in 5% gum arabic (25 mg/ml) and administered by gavage (100 mg/kg or an equal volume of vehicle). Two hours later, after placement of a right-heart catheter and an aortic thermistor (see Hemodynamic analysis and heart weights), rats were exposed to hypoxia (10.5% inspired O2 fraction), normoxia, or 15 min to remove cells and at 18,000 revolutions/min (28). Total protein concentrations were assayed by using the Bradford method. The left lungs were assayed by using a similar technique, except that the trachea was cannulated with a blunted 19-gauge needle. ET-1 was eluted by using methanol-water-acetonitrile (10:10:1) for the 25–50, and 152–50 μm. MT was calculated as MT (%) = 2 × MT/Vessel diameter × 100.

Statistical analysis. Differences between time-matched pairs of mean values were assessed by using unpaired t-tests.
Multiple-group comparisons were performed by using two-way analysis of variance. When F-ratios indicated statistical significance, post hoc analysis was done by using the Student-Newman-Keuls test. Differences were considered significant when P < 0.05. Values are presented as means ± SE.

RESULTS

Acute effects of bosentan. Two hours after gavage with bosentan (100 mg/kg), the acute pulmonary hypertensive effect of Big ET-1 in intact rats was completely blocked (Fig. 1). Bosentan had a similar blocking action on systemic hypertension induced by Big ET-1 (data not shown). The single dose of bosentan (100 mg/kg) blunted but did not completely abolish acute hypoxic vasoconstriction in intact rats (Fig. 2). Cardiac output was unchanged by acute hypoxia (data not shown).

Effects of bosentan on MCT-induced pulmonary hypertension. Saline-injected rats gavaged with bosentan (100 mg·kg⁻¹·day⁻¹) had slightly greater BWs than those given vehicle alone (Table 1), but otherwise there were no differences in heart weight, cardiac index, or hematocrit between the two groups. Among MCT-injected rats, BWs were lower than in saline-injected controls but were unaffected by administration of bosentan. As anticipated, MCT-injected rats had significantly elevated RV/BW and RV/(LV+S) values as well as RVSPs (Table 1, Fig. 3), indicating the development of RV hypertrophy and pulmonary hypertension after 21 days. Bosentan at a daily dose of 200 mg/kg, but not 100 mg/kg, significantly reduced the severity of both RV hypertrophy and pulmonary hypertension, as demonstrated by reductions in RV/(LV+S) and RVSP (Fig. 3). Neither MCT nor bosentan had any significant effect on LV mass, hematocrit, systemic blood pressure, or cardiac index (Table 1).

Rats injected with MCT had increased MTs of pulmonary vessels with diameters between 25–50 and 50–125 µm, but not 125–250 µm, compared with saline controls (Fig. 4). Bosentan (200 mg·kg⁻¹·day⁻¹) prevented the MCT-induced increase in MT of vessels with diameters between 25–50 and 50–125 µm. Bosentan (100 mg·kg⁻¹·day⁻¹) had no effect on MT of smaller pulmonary vessels (diameters of 25–50 and 50–125 µm) of saline-injected rats, but among 125- to 250-µm vessels, saline-injected rats that received bosentan had reduced MTs.

Effects of MCT and bosentan on ET-1 levels. Plasma levels of ET-1 were unchanged in rats 21 days after injection of MCT (Fig. 5A). Bosentan increased circulating ET-1 levels in both saline- and MCT-injected rats. ET-1 levels in lung homogenates from rats 21 days after MCT injection tended to be lower than those of saline-injected rats, but the difference was not statistically significant. Bosentan had no effect on lung homogenate ET-1 levels in either group (Fig. 5B).

Effects of bosentan on acute MCT-induced lung injury. Lung lavage protein concentration was 195 ± 39 µg/ml and wet-to-dry lung weight ratio was 4.80 ± 0.04 6 days after saline injection. These values increased to 351 ± 160 µg/ml and 4.96 ± 0.13, respectively, 6 days after MCT injection in rats gavaged with vehicle alone (P < 0.05 compared with saline). Daily gavage with 200 mg/kg bosentan had no effect on lung lavage protein concentration (366 ± 156 µg/ml) or wet-to-dry lung weight ratio (5.00 ± 0.08) 6 days after MCT injection (P was not significant compared with MCT-injected rats gavaged with vehicle alone).

Effects of bosentan on development of pulmonary hypertension. Eleven days after MCT injection, bosentan (200 mg·kg⁻¹·day⁻¹) prevented the increase in RVSP that occurred in MCT-injected rats, but no effect was seen on RV/(LV+S) (Fig. 6, A and B). At 21 days, RV/(LV+S) and RVSP were similar in bosentan-treated rats that were switched to vehicle alone 11 days after MCT injection, and in those treated with vehicle alone for the entire 3-wk period (Fig. 6, A and B). On the other hand, bosentan administered for only the last 10
of the 21 days after MCT injection was as effective as 21 days of bosentan in reducing RV/(LV+S). There was a trend toward a lower RVSP and RV/(LV+S) in the group receiving bosentan for only the last 10 days compared with that receiving it for only the first 11 days of the 3-wk period after MCT injection, but the difference was not statistically significant \( P < 0.05 \) for RVSP; \( P = 0.15 \) for RV/(LV+S).

### DISCUSSION

Our study is the first to show a statistically significant inhibition of MCT-induced pulmonary hypertension, pulmonary vascular thickening, and RV hypertrophy by a nonspecific ET blocker, thus strengthening the case that ET-1 plays a role in pathogenesis. Previous studies have used specific ETA blockade to inhibit pulmonary hypertension (20), leaving open the possibility that vasodilation caused by unopposed stimulation of the ETB1 receptor is responsible for the inhibition and that ET-1 is actually not involved in pathogenesis. On the assumption that bosentan effectively blocked both receptors in the present study, our findings eliminate this possibility from consideration. In addition, we also found no alterations in cardiac output attributable to bosentan administration, eliminating reduced blood flow as a possible contributor to the blunting of pulmonary hypertension.

In a prior study that posited a role for ET-1 in the pathogenesis of MCT-induced pulmonary hypertension, Miyauchi et al. (20) observed increases in plasma ET-1 levels preceding increases in pulmonary arterial pressure in MCT-injected rats. They also demonstrated

### Table 1. Body and heart weights, hematocrit, and systemic hemodynamics

<table>
<thead>
<tr>
<th>Protocol</th>
<th>n</th>
<th>Body Wt, g</th>
<th>RV/BW</th>
<th>(LV + S)/BW</th>
<th>Hct, %</th>
<th>MSBP, mmHg</th>
<th>CI, ml·kg⁻¹·min⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saline</td>
<td>15</td>
<td>378±11</td>
<td>0.56±0.01</td>
<td>2.01±0.03</td>
<td>44±1</td>
<td>119±6</td>
<td>216±12</td>
</tr>
<tr>
<td>Saline/bosentan</td>
<td>13</td>
<td>416±16*</td>
<td>0.53±0.02</td>
<td>1.97±0.04</td>
<td>42±1</td>
<td>114±9</td>
<td>221±15</td>
</tr>
<tr>
<td>MCT</td>
<td>20</td>
<td>358±9*</td>
<td>0.69±0.02*</td>
<td>2.01±0.03</td>
<td>43±1</td>
<td>103±5</td>
<td>215±14</td>
</tr>
<tr>
<td>MCT/bosentan (100 mg·kg⁻¹·day⁻¹)</td>
<td>7</td>
<td>350±12*</td>
<td>0.67±0.05*</td>
<td>1.99±0.07</td>
<td>44±1</td>
<td>118±10</td>
<td>216±48</td>
</tr>
<tr>
<td>MCT/bosentan (200 mg·kg⁻¹·day⁻¹)</td>
<td>17</td>
<td>362±8</td>
<td>0.63±0.02*</td>
<td>2.01±0.04</td>
<td>43±1</td>
<td>97±4</td>
<td>205±12</td>
</tr>
</tbody>
</table>

Values are means ± SE; n, no. of animals. RV/BW, right ventricular-to-body weight ratio; (LV + S)/BW, left ventricular plus septal-to-body weight ratio; Hct, hematocrit; MSBP, mean systolic blood pressure; CI, cardiac index; MCT, monocrotaline. *\( P < 0.05 \) compared with saline-to-body-treated animals. †\( P < 0.05 \) compared with MCT-treated animals.

Fig. 3. RVSP (A) and right ventricular-to-left ventricular plus septal weight ratios [RV/(LV+S)] (B) are shown in 2 saline-injected groups (left) and 3 monocrotaline (MCT)-injected groups (right). Values are means ± SE; n = 13–28 animals. Bosentan was administered by gavage at 100- or 200-mg/kg doses once daily. *\( P < 0.05 \) compared with saline controls. †\( P < 0.05 \) compared with MCT controls.

Fig. 4. Percent medial thickness (2 x medial thickness/vessel diameter x 100) for pulmonary vessels with diameters ranging from 25 to 50, 50 to 125, and 125 to 250 µm. Values are means ± SE; n = measurements made on 52–130 vessels/group from 4 lungs. Measurements were made on lung sections from saline-injected control rats gavaged with vehicle or bosentan (100 mg·kg⁻¹·day⁻¹) and MCT-injected rats gavaged with vehicle or bosentan (200 mg·kg⁻¹·day⁻¹). *\( P < 0.05 \) compared with saline control group. †\( P < 0.05 \) compared with MCT control group.
that the specific ET_A blocker BQ-123 inhibits MCT-induced pulmonary hypertension, RV hypertrophy, and pulmonary arterial medial wall thickening. Although lung homogenate and steady-state mRNA concentrations for ET-1 in the above-mentioned study dropped significantly from control levels 14 days after MCT injection, mRNA levels for ET-1 were elevated in the kidney. The authors speculated that the increase in circulating ET-1 levels derived from increased renal production and contributed to the pulmonary hypertension.

A recent report on telemetry in rats as a method for monitoring pulmonary arterial pressure observed trends for decreased pulmonary arterial pressures and RV hypertrophy in rats given bosentan (100 mg·kg⁻¹·day⁻¹ in saline and 200 mg·kg⁻¹·day⁻¹ in MCT-injected) or vehicle daily for 21 days. Values are means ± SE; n = 15–25 for plasma and n = 5–6 for lung homogenate levels. *P < 0.05 compared with saline control group. *P < 0.05 compared with MCT control group.

The specific ET_A blocker BQ-123 appeared to have achieved blockade of both ET-1 receptors in our study. Furthermore, the bosentan dose of 100 mg·kg⁻¹·day⁻¹ was sufficient to blunt chronic hypoxic pulmonary hypertension and completely block acute hypoxic pulmonary vasoconstriction in a previous study (2). The need to double the dose of bosentan to 200 mg·kg⁻¹·day⁻¹ to show a significant effect in our study may be related to slow absorption or rapid metabolism of bosentan in the strain of rats used or may suggest that ET-1 is less important in the pathogenesis of MCT-induced than of hypoxic pulmonary hypertension.

The specific mechanism by which ET-1 contributes to MCT-induced pulmonary hypertension remains unclear. Unlike Miyauchi et al. (20), we failed to detect any elevation of plasma ET-1 in MCT-injected controls, even 21 days after injection. However, like Miyauchi et al. (20), we observed a decrease in lung homogenate ET-1 levels, although the decrease was not quite statistically significant in our study. In addition, Miyauchi et al. (20) found a significant decrease in steady-state lung mRNA levels for ET-1. The question must be raised, then, How does ET-1 contribute to MCT-induced pulmonary hypertension if lung levels decrease and circulating levels remain steady? Regional variations in lung ET-1 production that decrease whole lung homogenate
concentrations but increase local concentrations, such as those adjacent to vascular smooth muscle, could offer an explanation. Alternatively, pulmonary vascular responsiveness to ET-1 could be upregulated, perhaps by alterations in the sensitivity or abundance of ETA receptors. Previous studies in isolated rat lungs have shown potentiation of pulmonary pressor responses to serotonin both 7 and 14 days after MCT pyrroline injection (14). Also, steady-state mRNA levels for the ETA receptor are increased in lung homogenates from rats with hypoxic pulmonary hypertension (17), although these have not been assessed in MCT-injected rats. In addition, Miyauchi et al. (20) observed an increase in oscillations induced by ET-1 in pulmonary arteries isolated from rats 14 days after MCT injection and speculated that they might reflect increased vascular responsiveness. By 25 days after MCT injection, however, the isolated pulmonary arteries had reduced contractility to ET-1 (20), suggesting that, if enhanced vascular responsiveness plays a role, it occurs transiently during the early development of pulmonary hypertension.

Regardless of the specific mechanism, blunting of MCT-induced pulmonary hypertension by bosentan is consistent with inhibition of vascular remodeling and possibly vasoconstriction. The dose of bosentan that was used completely blocked pulmonary vasoconstriction induced by Big ET-1 and partially blocked acute hypoxic vasoconstriction. This, combined with our observation that bosentan prevents the elevation of pulmonary arterial pressures seen 11 days after MCT injection before RV hypertrophy develops, is consistent with an inhibition of ET-1-induced vasoconstriction. In addition, our finding that bosentan inhibits MCT-induced pulmonary vascular medial thickening is consistent with blockade of the proliferative effect of ET-1 on vascular smooth muscle cells (15). This inhibition was most pronounced in smaller, peripheral vessels, where progenitor cells are thought to undergo transformation to smooth muscle cells, giving rise to neomuscularization (25).

The pathogenesis of MCT-induced pulmonary hypertension remains poorly understood. A liver-derived pyrrole metabolite of MCT is thought to acutely injure endothelial cells (1), causing diffuse endothelial vacuolization and swelling (24), metabolic dysfunction (21), and in situ thrombosis (19). Vascular permeability temporarily increases (28), but pulmonary hypertension and RV hypertrophy do not occur until 10–14 days after injection or ingestion, when diffuse inflammatory changes are apparent (19). This inflammatory process is accompanied by vascular and parenchymal histological changes (19), including vessel wall thickening, inflammatory interstitial changes, and the development of pulmonary function abnormalities typical of those seen with interstitial lung diseases (8). Multiple agents have been demonstrated to partially inhibit the severity of pulmonary hypertension and RV hypertrophy after MCT injection, including vasodilators (13, 22), corticosteroids (13), antiplatelet serum (12), and mild hyperoxia (11). This has led investigators to speculate that the pathogenesis of MCT-induced pulmonary hypertension is multifactorial, consisting of vasoreactive, inflammatory, cytokine, and hypoxic components.

Our findings indicate that ET-1 acts during the later inflammatory phase after MCT injection. We found that bosentan had no effect on the severity of the acute lung injury after injection, as assessed by lung lavage protein concentrations and wet-to-dry lung weight ratios. Furthermore, we found that bosentan inhibition of MCT-induced pulmonary hypertension tended to be greater during the latter half than the first half of the 3-wk period after injection. This suggests that the inhibitory effect of bosentan is unrelated to any early alteration of MCT metabolism by the liver that might have blunted the initial injury or delayed the development of pulmonary hypertension. This also suggests that ET-1 is involved mainly in the augmentation of pulmonary vascular reactivity and cellular proliferation that are thought to contribute to the development of pulmonary hypertension after the first week after MCT injection. However, the high dose of bosentan required and the relatively minor degree of inhibition achieved imply that, although ET-1 may contribute to MCT-induced pulmonary hypertension, other important agents and mediators are likely to be involved.

Finally, even though MCT-induced pulmonary hypertension has not been established as a suitable model for human idiopathic pulmonary hypertension, the inhibition of pulmonary hypertension by an oral once-a-day ET blocker raises the possibility that such agents may prove useful in the therapy of pulmonary hypertension in humans.

The authors thank M. Clozel of Hoffmann LaRoche, Basel, Switzerland, for the kind gift of bosentan, and J. Hayden for assistance in preparation of the manuscript.

This study was supported by a grant from the American Heart Association, Rhode Island Affiliate (N. S. Hill) and National Heart, Lung, and Blood Institute Grant HL-02613 (J. R. Klinger).

Address for reprint requests: N. S. Hill, Pulmonary Div., Rhode Island Hospital, 593 Eddy St., Providence, RI 02903.

Received 29 December 1996; accepted in final form 4 June 1997.

REFERENCES

6. Elton, T. S., S. Oparil, G. R. Taylor, P. H. Hicks, R. H. Young, H. J. In, and Y. F. Chen. Normobaric hypoxia stimulates endothel-


