Carbon Monoxide Inhalation Reduces Pulmonary Inflammatory Response during Cardiopulmonary Bypass in Pigs

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Background: Cardiopulmonary bypass (CPB) is associated with pulmonary inflammation and dysfunction. This may lead to acute lung injury and acute respiratory distress syndrome with increased morbidity and mortality. The authors hypothesized that inhaled carbon monoxide before initiation of CPB would reduce inflammatory response in the lungs.

Methods: In a porcine model, a beating-heart CPB was used. The animals were either randomized to a control group, to standard CPB, or to CPB plus carbon monoxide. In the latter group, lungs were ventilated with 250 ppm inhaled carbon monoxide in addition to standard ventilation before CPB. Lung tissue samples were obtained at various time points, and pulmonary cytokine levels were determined.

Results: Hemodynamic parameters were largely unaffected by CPB or carbon monoxide inhalation. There were no significant differences in cytokine expression in mononuclear cells between the groups throughout the experimental time course. Compared with standard CPB animals, carbon monoxide significantly suppresses tumor necrosis factor-α and interleukin-1β levels (P < 0.05) and induced the antiinflammatory cytokine interleukin 10 (P < 0.001). Carbon monoxide inhalation modulates effector caspase activity in lung tissue during CPB.

Conclusions: The results demonstrate that inhaled carbon monoxide significantly reduces CPB-induced inflammation via suppression of tumor necrosis factor α and interleukin-1β expression and elevation of interleukin 10. Apoptosis induced by CPB was associated with caspase-3 activation and was significantly attenuated by carbon monoxide treatment. Based on the observations of this study, inhaled carbon monoxide could represent a potential new therapeutic modality for counteracting CPB-induced lung injury.

This article is featured in “This Month in Anesthesiology.” Please see this issue of Anesthesiology, page 5A.


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Received from the Department of Anesthesiology and Critical Care Medicine, University Medical Center Freiburg, Germany. Submitted for publication July 25, 2007. Accepted for publication January 24, 2008. Supported by the Deutsche Forschungsgemeinschaft (DFG SCHL 604/2-1), Bonn, Germany, and departmental funding. Drs. Goebel and Siepe contributed equally to this work.

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Materials and Methods

Animals

German Landrace hybrid pigs weighing 28–32 kg received humane care in compliance with the Principles of Laboratory Animal Care formulated by the National Society for Medical Research and the Guide for the Care and Use of Laboratory Animals prepared by the Insti-
tute of Laboratory Animal Resources and published by the National Institutes of Health (publication No. 86-23, revised 1985). All procedures were performed in accordance with the German Animal Protection Law after obtaining the ethical permission of the local veterinary office (Regierungspraesidium, Freiburg, Germany).

**Experimental Protocol**

Healthy pigs were premedicated with intramuscular ketamine (20 mg/kg body weight [BW]) and midazolam (0.5 mg/kg BW). The animals were endotracheally intubated, and anesthesia was maintained with intravenous infusion of fentanyl (10 µg·kg BW⁻¹·h⁻¹) and propofol (4–6 mg·kg BW⁻¹·h⁻¹), and muscle relaxation was performed with cisatracurium (0.7–1 mg·kg BW⁻¹·h⁻¹). Basal saline volume administration was infused with 350 ml/h. The lungs were ventilated with a frequency of 14/min, a tidal volume of 8–10 ml/kg BW, and a positive end-expiratory pressure of 5 mbar. Inspired oxygen fraction was constantly 0.5. To monitor blood pressures as well as blood gas analysis, an arterial catheter was inserted in the right carotid artery. In addition, a pulmonary thermodilution catheter (7 French; Arrow, Reading, PA) was inserted into the pulmonary artery via an 8.5-French sheet (Arrow) in the right internal jugular vein. All animals received sternotomy after complete hemodynamic monitoring, and 300 U/kg BW heparin were administered. Initiation of CPB was achieved using a 24-French venous cannula in the right atrial appendage and a 14-French aortic cannula. The extracorporeal circulation unit (Stoeckert, Munich, Germany) was primed using 1,000 ml isotonic saline solution, 500 ml hydroxyethyl starch (6%), 75 ml mannitol, and 300 U heparin. CPB was maintained for 2 h with completely unloaded beating heart. Continuous positive airway pressure was kept at 5 mbar during this time. After CPB, a 30-s recruiting maneuver was performed, and standard ventilation was reestablished. CPB was removed, protamine matching the heparin dosage was administered, and 2 h of observation time (post-CPB; fig. 1, experimental design) followed. We collected blood gas samples at six defined time points: 0, 1, 2, 3, and 4 hours after CPB removal.

**Fig. 1.** Experimental protocol. All animals received sternotomy after complete hemodynamic monitoring. Cardiopulmonary bypass (CPB) was maintained for 2 h with completely unloaded beating heart. Continuous positive airway pressure was kept at 5 mbar during this time. CPB was removed, protamine matching the heparin dosage was administered, and 2 h of observation time followed. CO = carbon monoxide; SHAM = control group; SnPP IX = tin protoporphyrin IX.
time points (fig. 1): before CPB (pre-CPB); 10 min after initiation of CPB; at the end of CPB; and 15, 60, and 120 min post-CBP. Blood gas analysis included measurement of hemoglobin concentrations, electrolytes, and acid–base status. Five hundred milligrams of lung tissue was taken for further analysis at each time point. At the same points of time, hemodynamic parameters such as heart rate, mean arterial pressure, mean pulmonary pressure, central venous pressure, and pulmonary capillary wedge pressure were measured, and triplicate measurements of cardiac output (calculated as cardiac index) were performed with the thermodilution technique. Systemic and pulmonary vascular resistances were calculated.

The lung tissue was collected from three lung sites, i.e., cranial portion of the apical lobe, caudal portion of the apical lobe, and basal lobe. Samples were minced and stored at −80°C for protein and messenger RNA (mRNA) analysis. Animals were randomly assigned to three different intervention protocols and one post hoc group (fig. 1). The SHAM group (n = 3), serving as negative control, received sternotomy only. In the CPG group CPB (n = 7), serving as positive control, CPB was initiated and maintained for 2 h followed by 2-h observation period. Animals of the CPG + CO group (n = 7) were given carbon monoxide immediately after induction of anesthesia at a concentration of 250 ppm for 1 h.32,33 Animals of the post hoc CPB + CO + SnPP IX group (n = 7) were given the heme oxygenase inhibitor tin protoporphyrin IX (SnPP IX; 50 μmol/kg BW) immediately after induction of anesthesia for suppression of endogenous-derived carbon monoxide production. End- expiratory carbon monoxide concentration was monitored using a carbon monoxide analyzer (MicroSmokerlyzer; Breath CO Monitor, Bedfont, United Kingdom), and the content of carbon monoxide–saturated hemoglobin was measured photometrically during regular blood gas analysis. Inhalation of carbon monoxide was kept at 250 ppm until initiation of the CPB. The animals were killed 2 h after the end of CPB by myocardial potassium injection.

**Enzyme-linked Immunoabsorbent Assay**

Protein was extracted and enzyme-linked immunoabsorbent assay was performed following the manufacturer’s instruction (Quantikine; R&D, Minneapolis, MN). Protein concentration was determined using the Bradford Assay (Bio-Rad Laboratories, Munich, Germany).

**Northern Blotting**

Lung tissue was homogenized and total RNA was extracted using a one-step guanidinium thiocyanate–phenol–chloroform extraction reagent (Trizol®; Invitrogen, Carlsbad, CA). We separated 10 μg total RNA electrophoretically on 1% agarose gel and transferred it on a nylon membrane (Amersham, Braunschweig, Germany). Northern blotting was performed as previously described.36

**cDNA and Oligonucleotide Probes**

A full-length complementary DNA (cDNA) was constructed using a reverse-transcriptase polymerase chain reaction first strand cDNA kit (Fermentas, St. Leon-Rot, Germany). Polymerase chain reaction was performed using commercially synthesized specific oligonucleotides for TNF-α, IL-1β, and IL-10 (BigBiotech, Freiburg, Germany). The following specific primer sequences were used: TNF-α (478 bp): sense (5′-3′) TTC GTA CAT TCG CAC TTC GTG GAT ATC, antisense (5′-3′) TGA GTG GAT CAT CTT TCT CCA GCT; IL-1β (385 bp): sense (5′-3′) ACA GAA GTG AAG ATG GCC AAA GTC, antisense (5′-3′) TCA TGT GTC TCT GGA AGC TGT ATG; IL-10 (446 bp): sense (5′-3′) GCA TCC ACT TCC CAA CCA, antisense (5′-3′) CTG CCT CAT CTG CAT.

Polymerase chain reaction products were purified with QiaGen® Gel Extraction Kit and transformed into Escherichia coli bacteria via plasmid vector (pCR®.2.1 TOPO, TOPO TA Cloning; Invitrogen). Cloned plasmids were extracted according to the manufacturer’s instructions, and an EcoRI digestion was performed to isolate the cDNA insert. The probe was labeled with [α-32P]dCTP (Amersham) using the Prime it II Random Primer Labeling kit® (Stratagene, La Jolla, CA).

**Preparation of Mononuclear Blood Cells**

Blood samples were placed on top of Ficoll buffer and centrifuged at 1,800 rpm for 45 min. Mononuclear cells accumulated above the Ficoll, whereas erythrocytes formed a solid mass at the bottom of the tube. Mononuclear cells were gathered using a Pasteur pipette, washed in CliniMacs® (Miltenyi Biotec, Bergisch Gladbach, Germany) three times, and recentrifuged. RNA was extracted using the guanidinium thiocyanate-phenol-chloroform extraction, and total RNA was stored at −80°C until used again.

**RNase Protection Assay**

The ribonuclease protection assay was performed according to the manufacturer’s recommendation (Multi-Probe RPA; Becton Dickinson, Heidelberg, Germany). Using a customer requested template (supported by Becton Dickinson, Franklin Lakes, NJ), the assay was performed with 2 μg total RNA, extracted from peripheral mononuclear blood cells. The template components were IL-1β (257 bp); IL-6 (191 bp); IL-10 (316 bp); RANTES (regulated upon activation, normal T-cell expressed, and secreted) (172 bp); L32 (140 bp); and glyceraldehyde 3-phosphate dehydrogenase (125 bp).

**Fluorogenic Caspase Activity Assay**

Fluorogenic caspase activity assay was performed as previously described.37
Lung Histopathology

Lung histopathology evaluation was performed in pigs after lung tissues were removed from the animals and were placed in 10% neutral buffered formaldehyde overnight for fixation at room temperature. The tissues were processed into paraffin blocks, and 4-μm-thin microscopic sections were obtained using a microtome and placed on slides. Routine hematoxylin and eosin staining was performed. Histologic and morphologic changes induced by the interventions were evaluated by microscopy.

Quantitative and Statistical Analysis

Data were analyzed by a computerized statistical program (SigmaStat® for Windows Version 3.1; Systat Software Inc., San Jose, CA). The results are expressed as mean ± SD after normality was approved. Two-way analysis of variance for repeated measurements was used to compare parameters within one group. Two-way analysis of variance was used to compare the different groups. A P value less than 0.05 was considered statistically significant. Autoradiographs of Northern blots were evaluated by volume quantification and local median of gene expression and normalization against background using two-dimensional scanning (Personal Densitometer; Amersham).

Results

All animals used in this experimental project survived. Seventeen animals were randomly allocated to three groups, SHAM (n = 3), CPB (n = 7), and CPB + CO (n = 7), and one post hoc group, CPB + CO + SnPP IX (n = 7), added after the initial experiments. No animals were excluded at any time.

Blood Gas Analysis

At various time points before, during, and after CPB a complete arterial blood gas analysis was conducted, including acid–base status, electrolytes, hemoglobin, carboxyhemoglobin, and lactate concentration. Baseline levels of all parameters were not statistically different between all groups. Hemoglobin concentration in both CPB groups dropped by 20% at the onset of CPB and leveled off by the end without group differences, whereas in the SHAM group hemoglobin levels declined throughout the observation time by 10% because of dilution (data not shown). In both CPB groups, we detected a respiratory alkalosis during CPB with normalization after CPB (data not shown). Arterial oxygen pressure (PaO₂) was significantly lower in the CPB + CO group and the CPB + CO + SnPP IX group at 10 and 120 min CPB compared with the SHAM group (fig. 2A). In the post-CPB observation period, PaO₂ was not further affected by carbon monoxide inhalation (fig. 2A). As expected, carboxyhemoglobin levels in the SHAM group and the CPB group did not change significantly. Carbon monoxide inhalation (250 ppm) increased carboxyhemoglobin levels fivefold to sixfold up to peak values of 11.0 ± 2.9% after 1 h of inhalation (fig. 2B). After CPB, carboxyhemoglobin levels in the CPB + CO group and the CPB + CO + SnPP IX group decreased, reaching a value of 5.6 ± 2.3% at 120 min of the post-CPB observation period (fig. 2B). Other arterial blood gas parameters did not differ between groups.

Systemic Hemodynamics

Hemodynamic parameters are presented in table 1 and were largely unaffected by carbon monoxide inhalation. Heart rate significantly increased in the CPB group and the CPB + CO group at 15 and 60 min post-CPB compared with the SHAM group (table 1). Central venous pressure and pulmonary artery occlusion pressure remained unchanged throughout the study in all groups (table 1).

![Fig. 2. Arterial oxygen pressure (PaO₂, A) and carboxyhemoglobin levels (B) in control group (SHAM) (closed circles) and groups treated with cardiopulmonary bypass (CPB) (open circles), CPB + carbon monoxide (CO) (closed triangles), and CPB + CO + tin protoporphyrin IX (SnPP IX) (open triangles). Values are mean ± SD. * P < 0.05, CPB + CO versus SHAM and CPB.](image-url)
Systemic Effects of Inhaled Carbon Monoxide during CPB

The systemic effects of carbon monoxide on the mononuclear component of the systemic inflammatory response were evaluated by determining cytokine mRNA levels in peripheral mononuclear blood cells using an RNase Protection Assay. There were no significant differences in cytokine expression in mononuclear cells between the SHAM, CPB, or CPB + CO animals throughout the experimental time course (fig. 3, lanes 5–16). Lung tissue of a representative animal served as a positive control (fig. 3, lane 4). Housekeeping genes (glyceraldehyde 3-phosphate dehydrogenase) demonstrated equal amounts of loaded RNA (fig. 3, all lanes).

![Image]

**Table 1. Comparison of Hemodynamic Parameters in the Four Groups Studied During the Experimental Protocol**

<table>
<thead>
<tr>
<th>Time</th>
<th>Group</th>
<th>HR, min⁻¹</th>
<th>MAP, mmHg</th>
<th>mPAP, mmHg</th>
<th>CVP, mmHg</th>
<th>PCWP, mmHg</th>
<th>CI, l·min⁻¹·m⁻²</th>
<th>SVR, dyn·s·cm⁻²</th>
<th>PVR, dyn·s·cm⁻²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-CPB</td>
<td>SHAM</td>
<td>74 ± 16</td>
<td>95 ± 14</td>
<td>15 ± 1</td>
<td>5 ± 1</td>
<td>6 ± 1</td>
<td>2.7 ± 0.2</td>
<td>34 ± 6</td>
<td>3 ± 1</td>
</tr>
<tr>
<td></td>
<td>CPB</td>
<td>86 ± 16</td>
<td>85 ± 15</td>
<td>11 ± 1</td>
<td>4 ± 2</td>
<td>5 ± 1</td>
<td>2.5 ± 0.5</td>
<td>34 ± 13</td>
<td>3 ± 1</td>
</tr>
<tr>
<td></td>
<td>CPB + CO</td>
<td>93 ± 15</td>
<td>93 ± 13</td>
<td>13 ± 2</td>
<td>2 ± 2</td>
<td>6 ± 1</td>
<td>2.6 ± 0.5</td>
<td>34 ± 7</td>
<td>2 ± 1</td>
</tr>
<tr>
<td></td>
<td>CPB + CO + SnPP IX</td>
<td>87 ± 13</td>
<td>91 ± 16</td>
<td>12 ± 2</td>
<td>5 ± 3</td>
<td>6 ± 2</td>
<td>2.5 ± 0.4</td>
<td>33 ± 9</td>
<td>3 ± 1</td>
</tr>
<tr>
<td>Post-CPB 15 min</td>
<td>SHAM</td>
<td>67 ± 12</td>
<td>91 ± 7</td>
<td>15 ± 2</td>
<td>5 ± 1</td>
<td>7 ± 2</td>
<td>2.6 ± 0.2</td>
<td>34 ± 4</td>
<td>3 ± 0</td>
</tr>
<tr>
<td></td>
<td>CPB</td>
<td>106 ± 11†‡</td>
<td>79 ± 10</td>
<td>16 ± 5</td>
<td>4 ± 2</td>
<td>6 ± 2</td>
<td>2.8 ± 0.5</td>
<td>28 ± 8</td>
<td>4 ± 1</td>
</tr>
<tr>
<td></td>
<td>CPB + CO</td>
<td>94 ± 13‡</td>
<td>87 ± 7</td>
<td>15 ± 3</td>
<td>4 ± 3</td>
<td>7 ± 1</td>
<td>2.8 ± 0.6</td>
<td>34 ± 8</td>
<td>4 ± 2</td>
</tr>
<tr>
<td></td>
<td>CPB + CO + SnPP IX</td>
<td>103 ± 11†‡</td>
<td>94 ± 12</td>
<td>14 ± 3</td>
<td>5 ± 3</td>
<td>5 ± 3</td>
<td>2.5 ± 0.6</td>
<td>31 ± 7</td>
<td>4 ± 2</td>
</tr>
<tr>
<td>Post-CPB 60 min</td>
<td>SHAM</td>
<td>70 ± 16</td>
<td>88 ± 7</td>
<td>14 ± 2</td>
<td>6 ± 1</td>
<td>7 ± 2</td>
<td>2.5 ± 0.1</td>
<td>34 ± 3</td>
<td>3 ± 0</td>
</tr>
<tr>
<td></td>
<td>CPB</td>
<td>95 ± 19‡</td>
<td>73 ± 14</td>
<td>12 ± 1</td>
<td>3 ± 2</td>
<td>6 ± 2</td>
<td>2.4 ± 0.4</td>
<td>36 ± 7</td>
<td>3 ± 1</td>
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<tr>
<td></td>
<td>CPB + CO</td>
<td>89 ± 10†</td>
<td>80 ± 11</td>
<td>14 ± 2</td>
<td>4 ± 2</td>
<td>7 ± 1</td>
<td>2.5 ± 0.6</td>
<td>33 ± 8</td>
<td>3 ± 1</td>
</tr>
<tr>
<td></td>
<td>CPB + CO + SnPP IX</td>
<td>87 ± 11</td>
<td>88 ± 14</td>
<td>14 ± 4</td>
<td>4 ± 4</td>
<td>6 ± 2</td>
<td>2.3 ± 0.5</td>
<td>37 ± 6</td>
<td>4 ± 2</td>
</tr>
<tr>
<td>Post-CPB 120 min</td>
<td>SHAM</td>
<td>70 ± 17</td>
<td>84 ± 8</td>
<td>14 ± 2</td>
<td>7 ± 1</td>
<td>7 ± 2</td>
<td>2.5 ± 0.2</td>
<td>32 ± 4</td>
<td>3 ± 0</td>
</tr>
<tr>
<td></td>
<td>CPB</td>
<td>93 ± 13</td>
<td>76 ± 13</td>
<td>12 ± 1</td>
<td>3 ± 2</td>
<td>6 ± 2</td>
<td>2.2 ± 0.4</td>
<td>39 ± 7</td>
<td>3 ± 1</td>
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<tr>
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<td>92 ± 12</td>
<td>85 ± 11</td>
<td>13 ± 2</td>
<td>4 ± 2</td>
<td>7 ± 1</td>
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<td>2.2 ± 0.6</td>
<td>37 ± 4</td>
<td>3 ± 2</td>
</tr>
</tbody>
</table>

Values are mean ± SD.

* P < 0.05 vs. pre-cardiopulmonary bypass (CPB). † P < 0.05 vs. 120 min post-CPB. ‡ P < 0.05 vs. control group (SHAM) at the same time.

Cl = cardiac index; CO = carbon monoxide; CVP = central venous pressure; HR = heart rate; MAP = mean arterial pressure; mPAP = mean pulmonary artery pressure; PCWP = pulmonary capillary wedge pressure; PVR = pulmonary vascular resistance; SnPP IX = tin protoporphyrin IX; SVR = systemic vascular resistance.

![Image]

Fig. 3. Representative autoradiograph of RNase protection assay showing the time course of cytokine gene expression in mononuclear blood cells. A total of 10 µg RNA was used in each lane. CPB = cardiopulmonary bypass; CO = carbon monoxide; GAPDH = glyceraldehyde 3-phosphate dehydrogenase; IL = interleukin; RANTES = regulated upon activation, normal T-cell expressed, and secreted; Y = yeast transfer RNA.

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To evaluate the systemic toxic or beneficial effects of carbon monoxide on organ function, we determined plasma activity of lactate dehydrogenase (fig. 4A), creatine kinase (fig. 4B), myoglobin (fig. 4C), creatine kinase–muscle and brain subunit (fig. 4D), and N-terminal pro brain natriuretic brain peptide (fig. 4E) in plasma obtained from pigs after cardiopulmonary bypass (CPB), CPB + carbon monoxide (CO), and CPB + CO + tin protoporphyrin IX (SnPP IX) and time-matched control group (SHAM) animals. Data represent mean ± SD. *P < 0.05, CPB versus SHAM and versus CPB + CO. # P < 0.001, CPB + CO + SnPP IX versus CPB + CO.

Carbon Monoxide Inhalation Modulates Cytokine mRNAs and Protein Levels and Effector Caspase Activity in Lung Tissue during CPB

Cytokine mRNAs and protein levels in lung tissue were barely detectable in the SHAM group (data not shown). As shown in figure 6A, transcription of the TNF-α mRNA was also barely detectable at baseline in animals treated with CPB and with CPB + CO (fig. 6A, lanes 1 and 2). TNF-α mRNA expression increased significantly in the CPB group (fig. 6A, upper panel; 10 and 120 min; P < 0.05), both during and after CPB (fig. 6A, upper panel;
15, 60, and 120 min; \( P < 0.05 \). Animals of the CPB + CO group showed no significant differences to baseline.

Interleukin-1\( \beta \) mRNA transcription was significantly increased in the CPB animals (fig. 6B; 120 min CPB; \( P < 0.05 \) and 15, 60, and 120 min post-CPB; \( P < 0.001 \)).

Pulmonary TNF-\( \alpha \) protein levels remained unchanged during the experiments in SHAM animals (fig. 6C). In contrast, CPB significantly increased TNF-\( \alpha \) protein expression, reaching a maximum at the end of the observation time (fig. 6C). In the CPB + CO group, TNF-\( \alpha \) protein expression was significantly lower at 10 min CPB (fig. 6C; \( P < 0.05 \)) and during the post-CPB interval (fig. 6C; 60 and 120 min post-CPB; \( P < 0.05 \)). After blocking of the endogenous carbon monoxide production by SnPP IX, TNF-\( \alpha \) protein expression remained comparable to carbon monoxide–treated animals (fig. 6C; CPB + CO + SnPP IX).

Likewise, IL-1\( \beta \) protein expression increased significantly in the CPB group at 120 min post-CPB (1,591 pg/ml) compared with the SHAM group, whereas animals of the CPB + CO group showed protein expression...
comparable to that of SHAM animals (278 vs. 192 pg/ml; P < 0.001; fig. 6D). After blocking of the endogenous carbon monoxide production by SnPP IX, IL-1 protein expression remained comparable to carbon monoxide-treated animals (fig. 6D; CPB + CO and CPB + SnPP IX).

Interleukin-10 mRNA expression was unchanged during CPB (fig. 7A). In contrast, IL-10 mRNA expression was significantly induced by inhaled carbon monoxide treatment. At 120 min CPB and during the whole post-CPB period, IL-10 mRNA expression was 20-fold higher in the CPB + CO group compared with the CPB group (fig. 7A; 120 min post-CPB; P < 0.001).

To investigate whether apoptotic effects of the CPB-treated animals were associated with the activation of the crucial effector caspase-3 in the lungs, we performed a caspase-3 activity assay of the cytosols of these tissue samples by using a specific fluorogenic caspase-3 substrate (7-amino-4-methylcoumarin). Likewise, animals exposed to CPB showed a significant increase in caspase-3 activity during post-CPB compared with SHAM animals (fig. 7B; P < 0.05 vs. CPB). In contrast, animals treated with CPB + CO and with CPB + CO + SnPP IX had a caspase-3 activity not statistically different from SHAM animals (fig. 7B). Therefore, cell death induced by CPB was associated with caspase-3 activation and significantly attenuated by inhaled carbon monoxide treatment.

In addition, IL-10 protein levels in the SHAM and CPB-treated animals were unchanged during the whole experiment (fig. 7C). In contrast, levels of the antiinflammatory cytokine IL-10 were significantly higher in the CPB + CO group (602 vs. 70 pg/ml compared with CPB alone; fig. 7C, 60 min post-CPB [P < 0.05] and 120 min post-CPB [P < 0.001]). In addition, IL-10 protein expression was significantly higher in the CPB + CO + SnPP IX group (469...
vs. 70 pg/ml compared with CPB alone; fig. 7C; 60 min post-CPB \( P < 0.05 \) and 120 min post-CPB \( P < 0.001 \) and comparable to the levels of the CPB \( /H_1\text{CO} \) animals.

**Carbon Monoxide Inhalation Protects Lung Tissue during CPB**

Hematoxylin and eosin–stained lung tissue revealed no histopathology 120 min post-CPB in the SHAM animals (fig. 8A). CPB treatment caused atelectasis, edema, and infiltration of macrophages in the alveolar septa. Crucial destruction of the lung architecture was obvious at 120 min post-CPB (fig. 8B). Preoperative inhalation of 250 ppm carbon monoxide inhibited lung damage (fig. 8C). Suppression of endogenous carbon monoxide production via SnPP IX slightly altered the effect of inhaled carbon monoxide (fig. 8D).

**Discussion**

The use of CPB in cardiac surgery is often associated with pulmonary inflammation and dysfunction. The conditions of CPB, e.g., aortic cross clamping, excluded circulation of heart and lungs, the nutritive blood supply to the lungs continuous only via the bronchial arteries, contribute concurrently to the humoral and cellular processes leading to pulmonary dysfunction. After CPB, reperfusion leads to an inflammatory response. The incidence of significant pulmonary injury (e.g., acute respiratory distress...
syndrome) after cardiopulmonary bypass is rare (1.7%). The incidence of a lesser degree of pulmonary dysfunction, defined as a PaO₂/fraction of inspired oxygen ratio of 150 mmHg or less and chest radiography consistent with pulmonary edema, was 12%. Various interventions failed to blunt the bypass-induced inflammatory response and to decrease lung injury. Carbon monoxide, a powerful antiinflammatory drug, has been demonstrated to suppress the inflammation in a multitude of in vivo and transplantation studies. Therefore, the hypothesis of this study was that carbon monoxide may potentially serve as a novel intervention in reducing CPB-induced pulmonary inflammation.

Our findings support that inhaled carbon monoxide provides pulmonary antiinflammatory and antiapoptotic effects during CPB. In addition, and of greater importance, these effects occurred when carbon monoxide was administered only as a pretreatment, with the advantage of short exposure time, which results in a limited binding to hemoglobin, because the extent of carbon monoxide hemoglobin formation depends on the dose and the time of application. The effect had the following characteristics: (1) Systemic inflammation and adverse effects on extrapulmonary organs seem to be not important, because cytokine mRNA expression in mononuclear blood cells was not detectable and serum markers of hepatic, cardiac, or renal injury were also not detectable. (2) Carbon monoxide inhalation suppressed the CPB-induced pulmonary expression of the proinflammatory cytokines TNF-α and IL-1β. (3) Carbon monoxide inhalation significantly induced pulmonary IL-10 protein levels during the whole experiment. (4) Analysis of mRNA cytokine transcripts suggests a transcriptional regulation due to carbon monoxide-mediated effects. (5) Apoptosis in the lung is attenuated, because carbon monoxide inhalation inhibited effector caspase activity in lung tissue during CPB. These data suggest that the antiinflammatory and antiapoptotic properties of carbon monoxide may confer cytoprotection in a pig model of CPB-induced pulmonary inflammation and dysfunction.

In the lung, several studies have previously provided evidence that carbon monoxide mediates antiinflammatory and antiapoptotic effects during lung injury. For example, Choi et al. demonstrated that the same low concentration of inhaled carbon monoxide (250 ppm) as used in the current study significantly reduced TNF-α levels in lavage fluid in a rat model of ventilator-induced lung injury. In addition, the same group demonstrated that rats exposed to carbon monoxide exhibit a marked tolerance to lethal concentrations of hyperoxia. This increased survival was associated with highly significant attenuation of hyperoxia-induced lung injury as assessed by the volume of pleural effusion, protein accumulation in the airways, and histologic analysis. Otterbein et al. further demonstrated that carbon monoxide also exerts antiinflammatory effects in an in vivo model of lipopolysaccharide-induced inflammation. Carbon monoxide, even at low concentrations, selectively modulated the proinflammatory/antiinflammatory cascade of cytokines: Carbon monoxide inhibited the lipopolysaccharide-induced production of TNF-α, IL-1β, and macrophage inflammatory protein 1β while increasing IL-10 production. These data are in sharp contrast to similar experiments performed in humans, where carbon monoxide inhalation (10–500 ppm for 1 and 2 h after lipopolysaccharide infusion) did not
attenuate transiently increased plasma concentrations of inflammatory mediators (TNF-α, IL-6, IL-8, IL-10, IL-1). The pulmonary ischemia during bypass and the reperfusion injury after declamping in our setting may also be considered as an ischemia and reperfusion injury. In a model of renal ischemia and reperfusion in the rat, inhalation of carbon monoxide has been shown to normalize the inflammatory parameters and significantly reduced ischemia and reperfusion injury. Taken together, these data suggest that carbon monoxide is a selective and specific antiinflammatory modulator, and raises the question of which mechanisms are responsible for mediating these effects of carbon monoxide.

The suppression of cell apoptosis by carbon monoxide inhalation may represent a mechanism by which carbon monoxide provides protection against induced organ injury. Although the precise physiologic mechanism of antia apoptotic effects mediated by carbon monoxide has not yet been established, it is possible that this effect may be related to the powerful antioxidative and antiinflammatory functions of carbon monoxide. Inhaled carbon monoxide might limit the generation of reactive oxygen species, decrease the presence of free metal ions, and down-regulate proinflammatory cytokines. In addition, recent evidence suggested that carbon monoxide–treated animals showed an early up-regulation of the antiapoptotic gene Bcl-2 and down-regulation of proapoptotic genes (e.g., Fax and Bax). The up-regulation of antiapoptotic genes and down-regulation of proapoptotic genes can suppress apoptosis of pulmonary cells. Our study showed that pulmonary effector caspase activity decreased after carbon monoxide inhalation. Cell apoptosis serves as a useful marker of lung injury in response to oxidative stress and inflammation such as ischemia and reperfusion injury.

Hyperoxia may significantly alter normal cellular lung physiology, promoting formation of reactive oxygen species, activation of programmed cell death pathways, and expression of inflammatory cytokines. For the most part, up-regulated cytokines confer a degree of tolerance to hyperoxia via attenuation of cell death signaling pathways or augmentation of antioxidant activity. In our experiments, we used moderate hyperoxic levels with PaO2 values below 250 mmHg for a short period to obtain normoxia in the CPB + CO groups.

On the basis of the results presented here from animal studies, we cannot propose that carbon monoxide might possibly be used as an antiinflammatory agent in human cardiac surgery with CPB, because controlled human studies correlating carboxyhemoglobin to organ function do not exist. The use of a gas normally considered toxic must be carefully weighed. In this study, we used lower concentrations compared with the few human studies that examined the effects of continuous carbon monoxide inhalation on carboxyhemoglobin levels. For example, volunteers breathed carbon monoxide concentrations of 400–1,000 ppm until their carboxyhemoglobin levels reached 10–12% and were then assigned to hyperbaric oxygen therapy. A recently published clinical study by Mayr et al. showed no clinical signs of carbon monoxide toxicity after exposure of 250 and 500 ppm. Modest increases in carboxyhemoglobin levels equivalent to that resulting from cigarette smoking do not have any appreciable acute sympathetic and hemodynamic effects in healthy humans. Furthermore, the concentrations used here are comparable to the levels used in humans (0.03%) during measurement of lung diffusion capacity for carbon monoxide, a standard pulmonary function test. However, this study involved continuous carbon monoxide exposure, but it could be that these carbon monoxide concentrations might not be tolerated.

In conclusion, our findings support the theories that inhaled carbon monoxide provides pulmonary antiinflammatory effects during CPB and lead to a better understanding of the complex regulatory function of carbon monoxide in lung injury. Based on the observations of this study, it is tempting to speculate that inhaled carbon monoxide could represent a potential new therapeutic modality for counteracting CPB-induced lung injury.

The authors thank Alexander Hoctzel, M.D. (Department of Anesthesiology and Critical Care Medicine, University Medical Center, Freiburg, Germany), for his helpful assistance during the revision of the manuscript.

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