Carbon dioxide added late in inspiration reduces ventilation-perfusion heterogeneity without causing respiratory acidosis

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Brogan, Thomas V., H. Thomas Robertson, Wayne J. E. Lamm, Jennifer E. Souders, and Erik R. Swenson. Carbon dioxide added late in inspiration reduces ventilation-perfusion heterogeneity without causing respiratory acidosis. J Appl Physiol 96: 1894–1898, 2004. First published December 5, 2003; 10.1152/japplphysiol.00160.2003.—We have shown previously that inspired CO2 (3–5%) improves ventilation-perfusion (VA/Q) matching but with the consequence of mild arterial hypercapnia and respiratory acidosis. We hypothesized that adding CO2 only late in inspiration to limit its effects to the conducting airways would enhance VA/Q matching and improve oxygenation without arterial hypercapnia. CO2 was added in the latter half of inspiration in a volume aimed to reach a concentration of 5% in the conducting airways throughout the respiratory cycle. Ten mixed-breed dogs were anesthetized and, in a randomized order, ventilated with room air, 5% CO2 throughout inspiration, and CO2 added only to the latter half of inspiration. The multiple inert-gas elimination technique was used to assess VA/Q heterogeneity. Late-inspired CO2 produced only very small changes in arterial pH (7.38 vs. 7.40) and arterial CO2 (40.6 vs. 39.4 Torr). Compared with baseline, late-inspired CO2 significantly improved arterial oxygenation (97.5 vs. 94.2 Torr), decreased the alveolar-arterial PO2 difference (10.4 vs. 15.7 Torr) and decreased the multiple inert-gas elimination technique-derived arterial-alveolar inert gas area difference. These changes were equal to those with 5% CO2 throughout inspiration (arterial PO2, 102.5 Torr; arterial-alveolar PO2 difference, 10.1 Torr; and arterial-alveolar inert gas area difference, 0.21). In conclusion, we have established that the majority of the improvement in gas exchange efficiency with inspired CO2 can be achieved by limiting its application to the conducting airways and does not require systemic acidosis.

LOW CONCENTRATIONS (3–5%) of CO2 added during inspiration improve gas exchange and arterial oxygenation in normal lungs (8, 12). Our laboratory used the multiple inert-gas elimination technique (MIGET) to demonstrate that inspired CO2 improves arterial oxygenation by reducing ventilation-perfusion (VA/Q) heterogeneity (22). In further work, our group found that the influence of CO2 on VA/Q matching was associated with decreased regional pulmonary blood flow heterogeneity, as assessed by injected fluorescent microspheres (4).

Numerous studies in whole lungs and isolated airways and blood vessels reveal that CO2 and acidosis have several effects that have the potential to improve VA/Q matching (for review, see Ref. 23). They relax airway smooth muscle (3, 6, 7, 16, 20, 21, 27), whereas hypocapnic hyperventilation causes bronchoconstriction (12, 27). CO2 also increases collateral ventilation in many species (24) and enhances the surface tension-lowering properties of alveolar surfactant to increase lung compliance (31). These responses act in a direction adjusting regional ventilation to changes in perfusion. In a contributing fashion, the vascular effects of CO2 and acidosis include enhancement of hypoxic pulmonary vasoconstriction and in some species, including dogs and humans, hypercapnic acidotic pulmonary vasoconstriction (1, 2, 13); in this way CO2 and acidosis act to match regional perfusion to changes in ventilation.

Our interest in studying CO2 limited to the airways by adding it late in inspiration was stimulated by two aims and an otherwise neglected finding of improved arterial PO2 (PaO2) occurring with pulses of CO2 added to different phases of inspiration in a control of ventilation investigation (18). Our hypothesis (and first aim) was that CO2 could be added to the inspired gas late in inspiration and could improve VA/Q matching and do so without causing systemic respiratory acidosis. In giving CO2 in this manner, we wished to determine which of the sites of CO2 action (airways, vessels, and lung parenchyma) is most important. By adding CO2 late in inspiration, its effects could be largely restricted to the conducting airways, and effects of systemic respiratory acidosis contributing to better VA/Q matching could be avoided. These questions arose in part in response to a finding in awake tracheotomized ponies that late pulses of CO2 in inspiration caused no change in ventilation, but yet a 4-Torr decrease in the alveolar-arterial PO2 difference [(A-a)PO2], suggesting improved VA/Q matching (18).

METHODS

Animal instrumentation and support. The Animal Care Committee of the University of Washington School of Medicine, Seattle, Washington, approved all aspects of procurement, care, nutrition, experimental protocol, anesthetic use, and euthanasia in these experiments. Studies were performed on 10 healthy mixed breed dogs (weight range: 20–28 kg) in the supine position under barbiturate anesthesia (20–30 mg/kg iv sodium pentothal induction with supplemental doses, 1–2 mg/kg as needed every 30–60 min). The animals underwent intubation with a cuffed endotracheal tube. Femoral arterial and venous catheters were inserted, and a jugular 7-Fr thermodilution catheter was advanced into the pulmonary artery. Temperature was

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monitored by the pulmonary artery catheter. Ventilation was administered by a piston pump ventilator at a tidal volume of 12–13 ml/kg and a rate of 14–16 breaths per minute. Every 5 min, a single 30 ml/kg breath was provided to prevent atelectasis. Once an acceptable rate of ventilation was determined by arterial blood-gas analysis [arterial pH of 7.39–7.45 and arterial PCO₂ (PacO₂) of 35–40 Torr], no further changes in ventilator settings were made. After the experiment, the dogs were killed by an overdose of thiopental sodium.

**Inert gas exchange measurements.** Pulmonary and systemic arterial pressures, airway pressures, and mixed expired CO₂ and O₂ fractions (FiCO₂ and FiO₂, respectively) were continuously recorded on an eight-channel recorder (Hewlett-Packard, Palo Alto, CA). At specified intervals, pulmonary artery occlusion pressure, thermodilution cardiac outputs, and mixed expired FICO₂ and FeCO₂ (sampled from a 3-liter mixing box) were determined. FeO₂ and FeCO₂ in expired gas were measured by a mass spectrometer (Perkin-Elmer medical gas analyzer MGA-1100, Norwalk, CT). Blood pH and partial pressures of O₂ and CO₂ in arterial and mixed venous blood were measured on a blood-gas analyzer (Radiometer BMS-3, Radiometer America, Westlake, OH) maintained at 37°C and corrected to the pulmonary artery temperature. O₂ consumption (Vo₂) and CO₂ production (Vo₂) were calculated by analysis of expired gases using appropriate temperature, pressure, and water content corrections.

Respiratory gas exchange was assessed by analysis of arterial and mixed venous blood gases. In calculating (A–a)Po₂, the complete alveolar gas equation that incorporates inspired CO₂ fraction (FiCO₂) (25) was used.

The addition of CO₂ late in inspiration complicates the analysis of measured mixed expired CO₂ and O₂ for the calculations of Vo₂ and Vo₂. Because we know the tidal volume, the frequency, and the amount of 100% CO₂ added into the last half of inspiration, it is possible to calculate the mean weighted corrected inspired O₂ fraction (PICO₂) and FeCO₂ for purposes of calculating the Vo₂ and Vo₂ under the conditions of adding a gas into only a portion of the inspirate

\[
P_{\text{CO}_2}^{\text{corrected}} = \frac{(V_{\text{added gas}} \times F_{\text{CO}_2 \text{ added gas}}) + (V_i \times F_{\text{CO}_2})}{(V_{\text{added gas}} + V_i)}
\]

\[
F_{\text{O}_2}^{\text{corrected}} = \frac{(V_{\text{added gas}} \times F_{\text{O}_2 \text{ added gas}}) + (V_i \times F_{\text{O}_2})}{(V_{\text{added gas}} + V_i)}
\]

where \(V_{\text{added gas}}\) is the total volume of gas in the injected CO₂, FiCO₂ (0.000) and FiO₂ (0.209) are the inspired fractions of CO₂ and O₂ in the breath delivered by the ventilator, and FeCO₂ added gas (1.000) and FO₂ added gas (0.000) are the fractions of CO₂ and O₂ in the injected gas volume. On average these yielded a corrected FiCO₂ of 0.023 and a corrected FeCO₂ from the alveolar gas equation, we assumed that none of the added CO₂ reached the alveolar space. Consequently we corrected the measured values for mixed expired O₂ and CO₂ with the following equations

\[
F_{\text{FCO}_2}^{\text{corrected}} = F_{\text{FeCO}_2} - \frac{(V_{\text{added gas}} \times F_{\text{CO}_2 \text{ added gas}}) + (V_i \times F_{\text{CO}_2})}{(V_{\text{added gas}} + V_i)}
\]

\[
F_{\text{FO}_2}^{\text{corrected}} = F_{\text{FeO}_2}^{\text{measured}} \times \frac{(V_{\text{added gas}} + V_i) + (V_{\text{added gas}} \times F_{\text{O}_2 \text{ added gas}})}{V_i}
\]

**Inert gas exchange measurements.** VA/Q relationships were determined by MIGET (28, 29) using a constant infusion of a dilute solution of six inert gases (sulfur hexafluoride, ethane, cyclopropane, halothane, diethyl ether, and acetone) dissolved in 5% dextrose solution as described by Wagner and coworkers (28, 29). The gas extraction method of Wagner et al. (28) was used to determine inert gas tensions and solubilities in blood samples. Inert gas indexes were calculated from the 50-compartment model of Wagner et al. (29).

VA/Q heterogeneity was also assessed by the arterial-alveolar difference area [(a–A)D area], derived directly from the retention and excretion data (10). All inert gas data are the average of duplicate measurements.

**Experimental protocols.** Each dog underwent the same protocol, serving as its own control. After stabilization and a 20-min period of ventilation with room air, baseline hemodynamic (cardiac output, heart rate, systemic and pulmonary artery pressures), ventilation and respiratory gas exchange (arterial and mixed venous blood gases, minute ventilation, airway pressures, and Vo₂ and VC0₂), and inert gas exchange measurements (arterial and mixed venous blood gases, and mixed expired gas) were taken. After these measurements, the animal was ventilated with 5% CO₂ mixed into room air (as measured in the inspiratory gas by mass spectrometry), leading to an inspired O₂ of 19.9 ± 0.1%. After 20 min, all measurements were repeated, and then the animal was returned to room air ventilation. Next, the dogs received room air ventilation with a small quantity (4–15 ml) of CO₂ added to the last half of inspiration. This was done by smooth hand injection of the CO₂ over the full second half of the inspiratory phase. The order of the different CO₂ exposures was randomly determined by a coin toss.

**Statistical analysis.** All data are presented as means ± SD and were analyzed by repeated-measures ANOVA followed by Scheffé’s and Bonferroni/Dunn post hoc tests corrected for multiple comparisons of similar data sets and for comparisons over time. Differences between individual experimental points were analyzed by Wilcoxon’s signed-rank test.

**RESULTS**

Minute ventilation was fixed at 6.0 ± 1.5 l/min. The concentration of CO₂ during late CO₂ was 2.4 ± 0.8% of total tidal volume and 4.9 ± 0.06% during continuous inspired CO₂. The Fo₂ during continuous inspired CO₂ was 0.199 ± 0.006.

Hemodynamic and ventilatory effects of room air, 5% CO₂ and late-inspired CO₂ are listed in Table 1. Mean systemic blood pressure was unchanged by either CO₂ treatment, but mean pulmonary artery pressure increased significantly with 5% CO₂. Cardiac output increased with inspired 5% CO₂, approaching statistical significance (P = 0.06). Late-inspired CO₂ had no significant hemodynamic effects. Pulmonary artery occlusion pressure, peak airway pressure, hematocrit, and temperature did not significantly change in either experimental condition. For seven animals in which we collected expired gas for calculation of Vo₂ and VC0₂, there were no differences in Vo₂ (room air, 0.16 l/min; late CO₂, 0.16 l/min; 5% CO₂, 0.15 l/min). For VC0₂, there was no difference between room air and late-inspired CO₂.

| Table 1. Hemodynamic and ventilatory measurements |
|-----------------|-----------------|-----------------|-----------------|
|                  | Room Air        | Late CO₂        | 5% CO₂          |
| **SBP, mmHg**   | 112 ± 19        | 114 ± 23        | 116 ± 25        |
| **Ppa, mmHg**   | 16.3 ± 3.7      | 17.3 ± 3.3      | 19.8 ± 5.2*     |
| **HR**          | 140 ± 23        | 142 ± 26        | 147 ± 25        |
| **Q, l/min**    | 3.3 ± 0.9       | 3.4 ± 1.1       | 3.7 ± 1.4       |
| **PVR**         | 280 ± 120       | 290 ± 150       | 370 ± 190       |
| **Paw, mmHg**   | 9.6 ± 1.8       | 10.4 ± 2.0      | 10.7 ± 1.9      |
| **PAOP, mmHg**  | 7.4 ± 3.3       | 7.3 ± 3.9       | 7.5 ± 3.7       |

Values are means ± SD; n = 10 dogs. SBP, mean systemic blood pressure; Ppa, mean pulmonary artery pressure; Q, cardiac output; PAOP, pulmonary artery occlusion pressure; PVR, pulmonary vascular resistance; Paw, peak airway pressure; *P < 0.05 compared with baseline; †P < 0.01 compared with baseline.
late CO2 (0.15 vs. 0.16 l/min), but a small fall with 5% CO2 to 0.12 l/min (P < 0.05).

Table 2 provides respiratory gas exchange data. Both late-inspired CO2 and 5% CO2 produced a significant improvement in PaO2. A decrease in pH was significant in both experimental conditions, but late-inspired CO2 only decreased pH from 7.40 to 7.38, a clinically insignificant change. Late-inspired CO2 also had no significant effect on PaCO2, whereas continuous inspired 5% CO2 significantly increased PaCO2. Late-inspired CO2 improved mixed venous Po2 by 9.6 and alveolar O2 partial pressures, respectively; PaCO2, arterial CO2 partial pressures; pH, arterial pH. *P < 0.05 compared with baseline; †P < 0.01 compared with baseline.

late CO2 and 5% CO2, based on the seven dogs in which we had VVO2 and VCO2 measurements to calculate the respiratory quotient.

Table 3 shows MIGET gas data for eight dogs, in which reliable inert gas data were obtained. Data from two dogs were excluded because of a high residual sum of squares (>10). (a−A)D area for the six inert gases, a global measure of VA/Q heterogeneity, was equally and significantly reduced with both late CO2 and late CO2. The retention and excretion components of the inert gas (a−A)D area were reduced significantly with 5% CO2 but failed to attain significance at the P < 0.05 level for late CO2 (P = 0.11 and 0.07, respectively). 5% CO2 reduced the log standard deviations of the perfusion distribution and ventilation distribution approaching significance with both (P = 0.08 and 0.07, respectively). Shunt fraction and inert gas dead space were not affected by either late-inspired CO2 or 5% CO2.

Table 4 provides the mean retention and excretion values for the six inert gases in all three experimental conditions. For each gas, except acetone, there were statistically significant increases in excretion with 5% CO2. Otherwise there were no statistically significant differences in retention for either late CO2 or 5% CO2. However, inspection of Table 4 shows that for late CO2 the mean excretion values for all the inert gases except acetone were increased, suggesting a partial dose-response effect intermediate to that of 5% CO2.

Figure 1 plots the percentages of ventilation and perfusion across seven discrete V/Q ranges from shunt through dead space for the three conditions. These data show that both late CO2 and 5% CO2 cause a shift of ventilation out of high V/Q regions (V/Q = 10–100) into regions of midrange V/Q ratios (0.1–10).

DISCUSSION

The major finding of this study is that when CO2 is added during the latter half of inspiration, limiting it to the conducting airways, there is improved arterial oxygenation, a reduction in the (a−A)D area, and less V/Q heterogeneity without the development of systemic respiratory acidosis. From our analysis of the inert gas data, it appears that the effect of inspired CO2 (throughout inspiration and only during late inspiration) is largely to convert units of high V/Q ratio to more normal midrange values. The improvement in oxygenation with 5% CO2 added during only the latter half of inspiration was roughly half that observed with 5% CO2 throughout inspiration, but the improvement in V/Q matching was nearly equivalent. These findings demonstrate that local effects of CO2 in the lung contribute most to improved V/Q matching, but that systemic respiratory acidosis with 5% CO2 throughout inspiration further improves arterial oxygenation by changes
Late CO₂ was added by manually injecting a small aliquot (4–15 ml) of 100% CO₂ gas to the latter half of inspiration by following a pneumograph tracing. Thus there likely were small variations in breath-to-breath delivery of the CO₂ with respect to its appearance during the inspiration. Nevertheless, we were successful in restricting the delivery of CO₂ to the conducting airways because we essentially had no uptake of the added CO₂. The 0.02 pH change and 1 Torr rise in $P_{aCO_2}$ were trivial compared with the 0.12 pH unit and 15 Torr $P_{aCO_2}$ change with 5% CO₂ throughout inspiration. The concentration of CO₂ during late CO₂ was 2.4% when calculated for the entire breath but would be 4.8% for the final half of inspiration and hence similar in concentration to the continuous CO₂.

We studied dogs that were healthy by all outward appearances, but the inert gas data showed a greater degree of $V_{A}/Q$ heterogeneity than normal. Some of the dogs were studied in the fall when kennel cough is prevalent, and this may have contributed to some of the greater dispersion in our baseline $V_{A}/Q$ heterogeneity. Nevertheless, the effectiveness of inhaled CO₂ was evident regardless of the baseline state of gas exchange.

**Effects of CO₂ on gas exchange.** The nearly equal improvements in $V_{A}/Q$ matching observed with late-inspired CO₂ compared with continuous CO₂ establish that the majority of the effect of inspired CO₂ can be attributed to local effects in the lung. Addition of CO₂ in the latter half of inspiration exposes the conducting airways to a near-constant CO₂ tension throughout both phases of breathing without changing alveolar $P_{aCO_2}$. The high diffusibility of CO₂ leads to a lower extra- and intracellular pH within the airway epithelium and surrounding smooth muscle than during breathing of CO₂-free gas. Intracellular and extracellular acidoses directly relax bronchial smooth muscle (3, 6, 7, 16, 20, 21, 27). The bronchodilating effects of CO₂ may not be equal throughout the lung owing to differences in local ventilation and $V_{A}/Q$ ratio. Thus areas of low ventilation and $V_{A}/Q$ ratio may be intrinsically more bronchoconstricted and therefore could be more responsive to the dilating effect of a rise in local CO₂. In this manner, ventilation may be redistributed out of highly ventilated areas into poorly ventilated regions, with the net result that the ratio falls in high $V_{A}/Q$ regions and rises in low $V_{A}/Q$ regions. This is consistent with the changes in ventilation to $V_{A}/Q$ ratio shown in Fig. 1. We have recent and direct evidence for this pattern of regional ventilation redistribution in dogs ventilated with 5% CO₂ studied with aerosolized 1-μm fluorescent microspheres (5).

Although late-inspired CO₂ would be expected to have only airway effects, the distribution of regional perfusion may also be altered. Our data in dogs with fluorescent microspheres show that inspired CO₂ produces a more homogeneous distribution of regional perfusion (4). Transairway diffusion of CO₂ to the accompanying pulmonary arterioles with hypercapnic acidotic pulmonary vasoconstriction and/or CO₂-mediated augmentation of hypoxic pulmonary vasoconstriction offers an explanation for a late-inspired CO₂ effect on regional perfusion distribution despite that fact that inspired CO₂ only reaches the nonrespiratory bronchioles. Direct evidence for transairway gas exchange with accompanying pulmonary arterioles comes from human studies with H₂-sensitive platinum electrodes wedged into 2- to 3-mm pulmonary vessels (11, 19). The accompanying bronchi are sixth- to eighth-generation branches in the midportion of the conducting airway system (30). When subjects inhaled a single breath of H₂-rich gas, there was a within-breath response of the vascular electrode, in contrast to delayed signal consistent with alveolar H₂ uptake and return to the pulmonary artery via normal circulation when the electrode-tipped catheter was pulled back out of the wedged position (11, 19).

With CO₂ present in the entire breath, there is CO₂ uptake and systemic respiratory acidosis. Thus improvements in oxygenation and $V_{A}/Q$ matching may not entirely result from local effects of CO₂ in the lung. Systemic hypercapnia can increase
PaO₂ in two ways, independent of any change in V̇A/Q heterogeneity. First, the Bohr effect with systemic hypercapnic acidosis will lead to a higher PO₂ in both arterial and venous blood, for the same degree of hemoglobin saturation and blood O₂ content (26). Second, an elevated mixed venous PO₂ from the Bohr effect and an increased venous O₂ content arising from a slightly greater cardiac output but unchanged VO₂ (Table 1) will lead to a higher PaO₂ for any degree of fixed V̇A/Q mismatch (9). Last, systemic hypercapnia may improve V̇A/Q matching via neural reflexes involving airways and pulmonary vessels (23) arising from the peripheral and central chemoreceptors, as is true for peripheral chemoreceptor-mediated reduction of hypoxic pulmonary vasoconstriction (32).

In conclusion, our data establish that increases in CO₂ limited to the conducting airways during inspiration improve gas exchange in the lungs of dogs because of a decrease in V̇A/Q heterogeneity. In normal lungs, an improvement in arterial oxygenation of only 4 Torr, and an equivalent drop in chemoreceptors, as is true for peripheral chemoreceptor-mediated pulmonary vascular responses (37), will lead to a higher PaO₂ for any degree of hypercapnia (26). Second, an elevated mixed venous P O₂ from blood, for the same degree of hemoglobin saturation and blood flow, for the same degree of hypercapnia (26). Second, an elevated mixed venous P O₂ from hypercapnia with systemic hypercapnic acidosis may yield more significant improvements when V̇A/Q mismatching is greater. Last, addition of CO₂ into the latter half of inspiration offers a potential therapeutic strategy to enhance gas exchange and suppress local inflammatory events in lung injury when patients cannot tolerate further increases in the latter half of inspiration in many states of lung dysfunction may yield more significant improvements when V̇A/Q mismatching is greater. Last, addition of CO₂ into the latter half of inspiration offers a potential therapeutic strategy to enhance gas exchange and suppress local inflammatory events in lung injury when patients cannot tolerate further additional respiratory acidosis with tidal volume reduction (lung-protective ventilation or permissive hypercapnia) or CO₂ added uniformly into the inspired gas (15, 17).

GRANTS

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REFERENCES