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apparatus and techniques

A lung model of carbon dioxide concentrations with mechanical or spontaneous ventilation

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Modifications of a commercially available mechanical lung model (Vent-Aid Training Test Lung, Michigan Instruments, Inc., Grand Rapids, MI) enabled the study of CO_2 concentration, distribution, and washout curves. An additional modification allowed either simultaneous or separate study of spontaneous ventilation and work of breathing.

A popular lung model useful for education and research that mimics the effects of compliance and airway resistance is the Vent-Aid Training Test Lung (Michigan Instruments, Inc., Grand Rapids, MI) This test lung consists of two independent bellows, the compliance of each being determined by the distance from the pivot, where the compliance springs are set. The flow resistance in each lung depends on the diameter of the tube chosen as the bronchus. To study either CO_2 concentration and distribution or spontaneous ventilation at ambient or positive pressures, e.g., continuous positive airway pressure (CPAP), or distribution of ventilation, we made several modifications to the test lung. In particular, we want to emphasize that we approximated each bellows as a lung with a separate, assignable resistance, compliance, and CO_2 concentration. We grouped the different characteristics of individual alveoli into the overall properties of the lung. Although not an exact physiologic reproduction, the model still provides useful insight into the interactions between respiratory variables (1).

MATERIALS AND METHODS

We replaced an aluminum disc on the top surface of one of the bellows of the lung model (an oxygen sensor port) with a disc of similar dimensions that included two 0.25-inch diameter metal tubes ending with Luer lock-type connectors (Fig. 1). A gasket was used to keep the bellows airtight. We fastened a three-way stopcock to each tube; one tube was the inlet for CO_2, and the other tube could be used to simulate a bronchopleural cutaneous fistula (stopcock open to atmosphere) or to monitor simulated alveolar CO_2 tension or inflating pressure. A flowmeter controlled the influx (production) of CO_2. Alveolar and fractional end-tidal CO_2 levels were simulated by adjusting the CO_2 production and the minute ventilation. We modified the deadspace of the test lung by changing the insertion depth of the endotracheal tube into a 1.5-inch bore transparent plastic tube (trachea).

A small electric fan that ensured even distribution of CO_2 throughout the bellows was positioned inside the bellows. By removing the mounting screws on the top surface, we could drop the fan into the bellows. An additional hole was then drilled into the aforementioned modified disc through which the electric fan wires were threaded and sealed in place with silicone glue. Sufficient slack in the wires was allowed so that

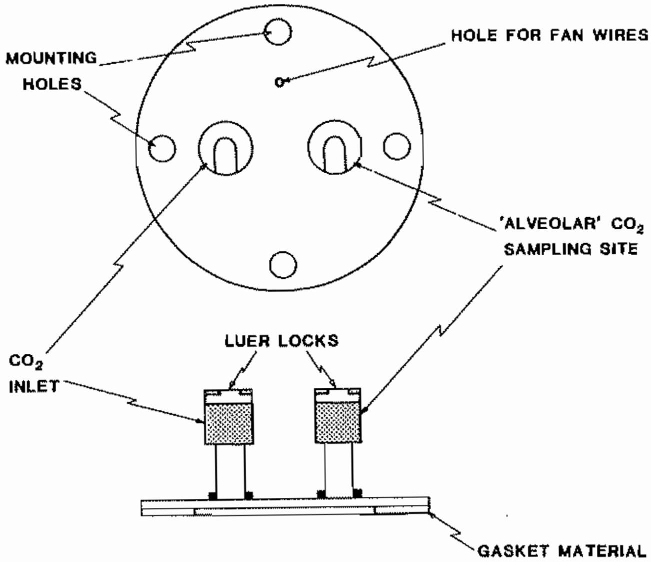

FIG. 1. Modifications to the oxygen sensor port to allow CO_2 flow into and sampling from the test lung.

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at full extension of the bellows, i.e., inflation to maximal tidal volumes, the fan was not unseated. Shims were added to the base of the fan to elevate it slightly with respect to the base of the lung. This ensured adequate entrainment by the fan.

The modifications that enabled modelling of spontaneous ventilation resemble those described by Op't Holt et al (2). Because this lung model has two bellows, one can be used to drive the other. The driving bellows was mechanically inflated with a piston-operated ventilator (Emerson 3-PV, Cambridge, MA); the contralateral bellows received the controlled inflow of CO_2 (Fig. 2).

An important difference in our model was that the two bellows were not bolted together. Instead, we screwed a metal bar to the top of the driving bellows. This bar was shaped so that when the driving bellows was inflated by the ventilator, the metal bar lifted the contralateral bellows and, thus, simulated spontaneous inhalation. On the downstroke of the ventilator, the driving bellows was lowered to resting volume, and the metal bar lost contact with the contralateral bellows. The contralateral bellows then passively recoiled (exhalation) at a rate determined by the airway resistance and compliance settings. Spontaneous breathing rate, tidal volume, inhalation to exhalation time ratio, and inspiratory flow rate of the model were adjusted by controls on the driving ventilator.

RESULTS

The recordings exhibited features resembling spontaneous positive pressure ventilation with CPAP and continuous mechanical ventilation (CMV) (Fig. 3). Airway pressure characteristically decreased during spontaneous inhalation with CPAP and increased during mechanical inhalation with CMV. The flow wave during inhalation with CPAP resembled a sinusoidal pattern.

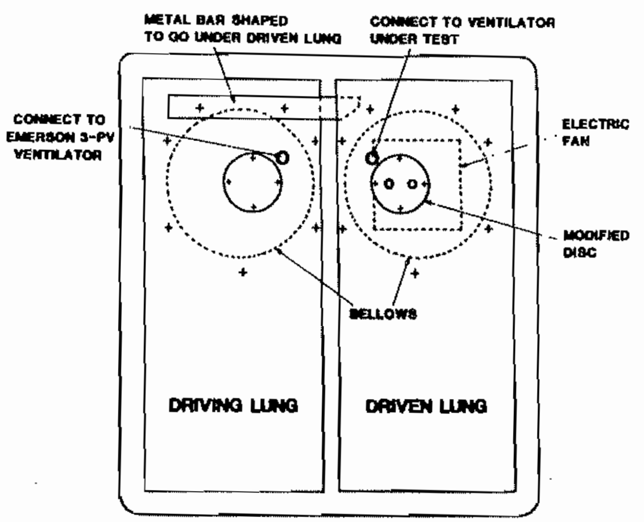

FIG. 2. Vent-Aid Training Test Lung (TTL) modified to permit CO_2 concentration and spontaneous ventilation studies.

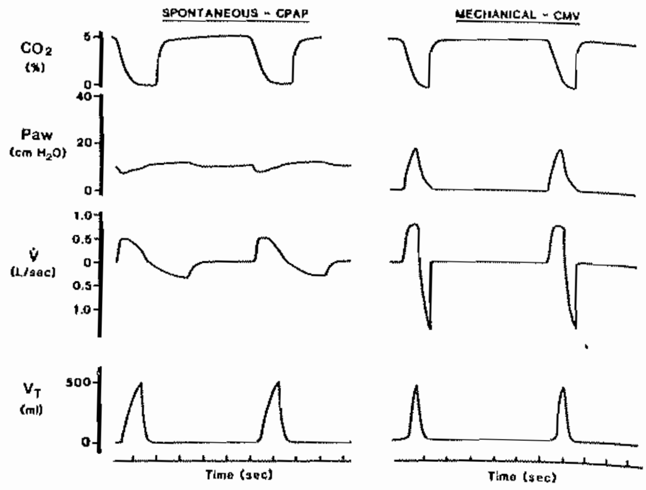

FIG. 3. Capnographic, airway pressure (Paw), flow ($\dot{V}$), and tidal volume (V_T) traces obtained with a modified lung model during spontaneous ventilation with CPAP and during CMV.

For both modes, conditions were set to ventilate with similar tidal volumes. CO_2 inflow into the lung model and minute ventilation were adjusted to yield fractional end-tidal CO_2 level of 5% under both ventilatory conditions. Although a reasonable similarity is apparent between the respiratory waveforms produced by the model and those expected in a patient for both CPAP and CMV, caution should be exercised in applying this model to situations where hemodynamic and alveolar interactions are significant. For example, this model cannot mimic oxygen consumption. The effects of increased mean airway pressure on venous return to the heart and cardiac output are not reproducible. The model is also not intended to examine ventilation/perfusion inequalities.

DISCUSSION

Our modified lung model has enabled us to study CO_2 washout rates during CMV and the inspiratory flow-resistive work of breathing by means of pressure-volume loop analysis (3). The external flow-resistive work of breathing during spontaneous ventilation with different types of ventilator CPAP systems may also be compared with this modified lung model. Our model is more complex than that described by Banner et al. (4) and enables us to evaluate the effects of compliance and resistance when the external flow-resistive work of breathing is analyzed during CPAP.

CO_2 rebreathing with anesthetic circuits during both CPAP and CMV can also be studied with this system. The level of rebreathing is indicated by the magnitude of the deviation above 0% CO_2 of the capnograph trace during inhalation. Variables can then be altered to determine their effects on rebreathing of CO_2.

CO_2 washout curves provide valuable information about the efficacy of a ventilatory system. Washout of CO_2 can be mimicked with our model by first flushing the system with a known concentration of CO_2, and then interrupting the CO_2 influx while simultaneously starting either CPAP or CMV.

The flow rate of 100% CO_2 into the lung can be set to simulate any CO_2 minute production. A capnograph sampling flow rate equal to the CO_2 inflow rate results in a balance of infused and sampled gas. Lower CO_2 inflow and sampling flow rates as well as lower compliances and higher flow resistances can be used to model ventilation of children.

The influences of compliance, resistance, tidal volume, and CO_2 production on the distribution of ventilation can also be examined. Distribution of ventilation can be studied by providing each bellows with a fan and a known inflow of CO_2 (e.g., 100 ml/min of 100% CO_2 each). (This also requires that the metal bar be removed to make the lungs independent of each other.) Adjusting the resistance and compliance of each bellows independently simulates lungs with unequal time constants (5). By measuring the P_{CO_2} of each bellows during mechanical ventilation, distribution of ventilation can be inferred. Lower P_{CO_2} implies good regional ventilation, and higher P_{CO_2} implies poor regional ventilation for the same CO_2 inflow rate to each lung. This is in accordance with the equation for regional minute ventilation:

$$\text{regional minute ventilation} \propto \text{regional } \dot{V}_{CO_2}/P_{CO_2}$$

where $\dot{V}_{CO_2}$ is the flow of CO_2. Since regional $\dot{V}_{CO_2}$ is kept constant in the model, regional minute ventilation is inversely proportional to P_{CO_2}.

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