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Wasted Ventilation Measured In Vitro *with Eight Anesthetic Circuits with and without Inline Humidification*

Charles J. Coté, M.D., A. John Petkau, Ph.D.,† John F. Ryan, M.D.,‡ James P. Welch, B.S.E.E., C.C.E.§*

Compression of gases (Boyle's law) and circuit compliance are major determinants of anesthesia circuit function. The materials of which circuits are constructed and the use of heated humidifiers may result in clinically important variations in delivered minute ventilation ($\dot{V}E$) secondary to variations in compression volume. We examined eight anesthetic circuits both with and without a heated humidifier in an *in vitro* setting. Compression volume was determined with a large calibrated syringe. Circuit efficiency was determined by measuring $\dot{V}E$ at multiple peak inflation pressures (PIP) while using a pediatric ventilator with fixed $\dot{V}E$, respiratory rate, fresh gas flow, and I/E ratio.

As expected, both compression volume and delivered $\dot{V}E$ highly correlated with the type of circuit and the pressure at which it was examined ($P < 0.001$). Mapleson D circuits had the lowest compression volume and were the most efficient circuits ($P < 0.0001$). Pediatric circle systems were intermediate and adult circle systems had the largest compression volume and were the least efficient. Humidifiers uniformly increased compression volume.

The following conclusions were drawn: 1) the anesthetic circuit, its material, and the pressure at which it operates are important determinants of circuit function; 2) humidifiers increase compression volume; 3) Mapleson D circuits had the lowest compression volume and therefore were the most efficient; 4) highly compliant adult circuits may result in compression volume losses that exceed the tidal volume of a pediatric ventilator; 5) humidifiers with low volume and rigid tubing should have the least effect on minute ventilation; and 6) highly compliant adult circuits when used in the care of infants and small children must be used with caution. (Key words: Anesthesia: pediatric. Equipment: circuits; humidifiers. Physics: gas compression. Ventilation: wasted.)

THE EFFECTS of compression volume and circuit compliance on delivered minute ventilation ($\dot{V}E$) have been recognized for a long time.[1–9] The use of heated humidifiers and disposable circuits makes an understanding of how these might influence circuit performance central to the safe anesthetic management of small children. Therefore, we examined several anesthetic circuits in an *in vitro* setting to determine ventilatory losses (circuit efficiency) as a result of compression of anesthetic gases (compression volume) and stretching of the circuit (compliance volume).

Methods and Materials

Study A

Eight anesthetic circuits with tubing for connections with a ventilator and heated humidifier (Bennett Cascade I) filled with water to the top line were examined. The volume of the carbon dioxide absorber minus the crystals was determined with water as was the volume of each circuit. Three modified Mapleson D circuits ("Bain" [Respiratory Care, Inc.], "Piggy Back" [Vital Signs], and our own version of the Mapleson D) were studied with a humidifier. Five circle systems (adult and pediatric rubber [Ohio], adult and pediatric plastic [Dryden], adult wire reinforced [Bennett]) were studied both with and without a humidifier. Each circuit was pressurized six times at each pressure to 10, 20, 30, 40, and 50 cm of water by means of a 1,000-ml calibrated syringe and the volume needed to achieve this recorded. These measurements estimated the combined effects of circuit distensibility (compliance) and gas compression (Boyle's Law). For purposes of discussion, this is defined as compression volume.

Study B

Each of the circuits in study A were examined with a Fraser-Harlake ventilator (pediatric bellows) with $\dot{V}E$ set at 5 l/min, a rate of 15 breaths/min, and 5 l/min oxygen inflow. Peak inflation pressure (PIP) was fixed at 10, 20, 30, 40, and 50 cmH_2O with a Bourns lung simulator (LS122). Delivered $\dot{V}E$ was measured proximal to the lung simulator with a Large Dial Wright respirometer. The inspired/expired ratio (I/E) was set at 1:2; six measurements were made successively at each PIP. These measurements determined the efficiency of dynamic circuit function. Efficiency reflects delivered $\dot{V}E$; the greater the $\dot{V}E$ at a particular PIP, the more efficient the circuit.

Data were analyzed by least-squares analysis, residual analysis, analysis of variance, the F statistic, and *t* tests where appropriate. Because 19 comparisons were carried out, a conservative approach would be to consider differences significant only when $P < 0.0026$ ($0.05/19 = 0.0026$).[10]

* Assistant Professor of Anaesthesia, Harvard Medical School.

† Visiting Associate Professor, Department of Biostatistics, Harvard School of Public Health.

‡ Associate Professor of Anaesthesia, Harvard Medical School.

§ Clinical Engineering Manager, Department of Anesthesia, Massachusetts General Hospital.

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Address reprint requests to Dr. Coté: Department of Anesthesia, Massachusetts General Hospital, Boston, Massachusetts 02114.

TABLE 1. Compression Volume (ml) *versus* Pressure (cmH_2O)*

Circuit	Peak Inflation Pressure (cmH_2O) 10	20	30	40	50
Mapleson D circuits					
Bain (H)	20	60	100	120	167
Piggy Back (H)	27	67	127	147	180
Our own (H)	27	53	94	120	160
Circle circuits					
Adult rubber	127	240	353	487	600
Adult rubber (H)	147	267	380	547	687
Adult plastic	74	147	220	294	347
Adult plastic (H)	100	187	274	360	447
Adult wire	53	127	187	240	294
Adult wire (H)	74	147	220	280	353
Pediatric rubber	53	107	167	207	260
Pediatric rubber (H)	67	133	200	267	320
Pediatric plastic	53	113	174	233	267
Pediatric plastic (H)	67	140	200	274	333

* This table presents the mean volume of compressed oxygen of six determinations at each peak inflation pressure. The presence of the letter H indicates that the study was carried out with the use of a heated humidifier (see text for details).

TABLE 3. *P* values for *t* Tests Comparing Various Circuits with Humidifier (H)* and without Humidifier

Circuits Compared	*P* Values: Compression Volume	Delivered Ventilation
Mapleson D Circuits		
Bain (H)—Piggy Back (H)	0.60	0.14
Bain (H)—our own (H)	0.94	0.18
Piggy Back (H)—our own (H)	0.54	0.87
All Mapleson D-all circles	<0.0001	<0.0001
Circle circuits		
All adult—all pediatric	<0.0001	0.007
All adult (H)—all pediatric (H)	<0.0001	0.27
Adult rubber—adult rubber (H)	0.15	0.02
Adult plastic—adult plastic (H)	0.06	0.26
Adult wire—adult wire (H)	0.26	0.03
Pediatric rubber—pediatric rubber (H)	0.21	0.005
Pediatric plastic—pediatric plastic (H)	0.26	0.001
Adult rubber—adult plastic	<0.0001	0.51
Adult rubber (H)—adult plastic (H)	<0.0001	0.04
Adult rubber—adult wire	<0.0001	0.03
Adult rubber (H)—adult wire (H)	<0.0001	0.008
Adult plastic—adult wire	0.24	0.10
Adult plastic (H)—adult wire (H)	0.06	0.52
Pediatric rubber—pediatric plastic	0.76	0.70
Pediatric rubber (H)—pediatric plastic (H)	0.87	0.47

* The presence of the letter H indicates that the study was carried out with the use of a heated humidifier.

Results

The compression volume and delivered minute ventilation ($\dot{V}E$) are presented in tables 1 and 2; both were correlated highly to the type of circuit and the pressure at which they were examined ($P < 0.001$). Study A revealed that the Mapleson D systems with a humidifier performed nearly identically and, as a group, had smaller compression volumes than the circle systems with or without a humidifier (table 1). There was no difference between the two pediatric circle systems either with or without a humidifier (table 3). There were no differences between the adult plastic or wire-reinforced circuit both

TABLE 2. Delivered Ventilation (ml/min)*

Circuit	Circuit Volume (ml)	Peak Inflation Pressure 10	20	30	40	50
Mapleson D Circuits						
Bain (H)	2,060	7,687	5,932	5,073	4,278	3,362
Piggy Back (H)	2,040	6,353	5,410	4,967	4,108	3,170
Our own (H)	2,430	6,348	5,410	5,148	4,185	3,170
Circle circuits						
Adult rubber	4,580	5,927	4,575	2,227	—	—
Adult rubber (H)	6,270	5,557	3,455	951	—	—
Adult plastic	4,025	6,052	4,795	3,263	1,412	—
Adult plastic (H)	5,530	5,655	4,387	2,673	1,248	—
Adult wire	4,280	6,217	5,052	4,012	2,720	1,632
Adult wire (H)	5,870	5,993	4,428	2,993	1,462	—
Pediatric rubber	3,920	6,198	5,128	4,183	3,120	1,958
Pediatric rubber (H)	5,510	5,865	4,438	3,005	1,432	—
Pediatric plastic	3,855	6,245	5,123	4,145	2,793	1,685
Pediatric plastic (H)	5,360	5,847	4,257	2,497	1,137	—

* This table presents the mean delivered minute ventilation for each circuit of six determinations at five different peak inflation pressures. The presence of the letter H indicates that the study was carried out using a heated humidifier. All circuits were examined with the same ventilator, with the same settings, and fresh gas flow (see text for details). Blank spaces represent pressures at which no flow was recorded. The volume (ml) of each circuit minus water in the humidifier and crystal in the carbon dioxide absorber are presented; note that the humidifier adds approximately 1,500 ml to each circuit.

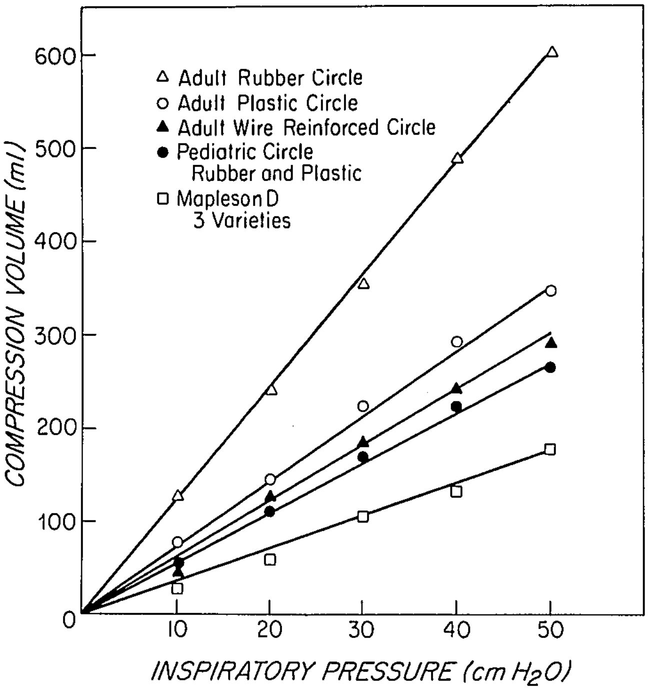

FIG. 1. This figure presents the compression volume (ml) *vs.* peak inspiratory pressure (cm H_2O) as determined with a 1,000-ml calibrated respiratory syringe. The Mapleson D circuits as a group had the lowest compression volume and the lowest ventilation losses. The pediatric rubber and plastic circle systems had the next lowest compression volume and were nearly identical to the adult wire-reinforced circuit. The adult plastic circuit had the second-largest compression volume losses, while the adult rubber circuit was the least efficient and had the largest compression volume.

with or without a humidifier; the latter was nearly identical to the pediatric circle systems. The adult rubber circuit had the largest compression volume, which was significantly greater than the others. Figure 1 graphically represents these comparisons.

Study B revealed all Mapleson D systems with a humidifier to be more efficient than the circle systems either with or without a humidifier. The pediatric circle systems performed nearly identically both with or without a humidifier; these systems were affected more greatly by the addition of a humidifier than the adult systems (fig. 2; Table 3). Addition of a humidifier resulted in a decrease in $\dot{V}E$ for each system examined. The adult rubber circuit performed the least efficiently of any circuit tested (fig. 3).

Discussion

Actual delivered ventilation may be different from that electronically set on a ventilator or from that seen by excursion of the bellows, for several reasons.[1-4,11] An augmentation may occur with fresh gas flows into the circuit, which are added to the volume delivered by the ventilator during inspiration. The significance of this effect is dependent on the rate of fresh gas flow, I:E ratio, and the type of ventilator used.[11] A reduction in delivered ventilation may result from both compression of the gases (Boyle's law $P_1 \times V_1 = P_2 \times V_2$) and distensibility (compliance) of the breathing circuit.[1-4] In the former situ-

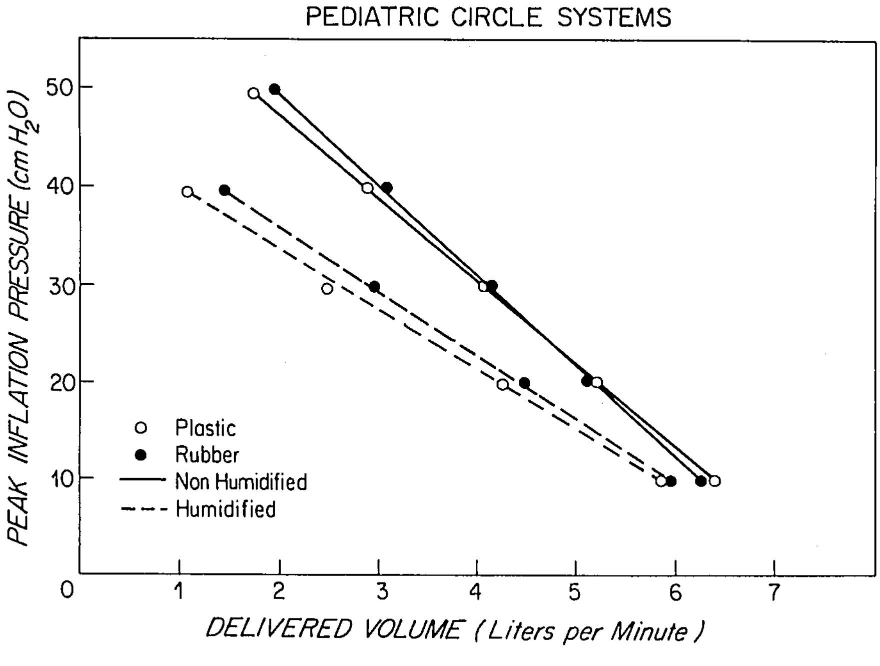

FIG. 2. This figure illustrates the delivered minute ventilation for two pediatric circle circuits (rubber and plastic). The performance of these circuits was nearly identical both with and without a humidifier. Note, however, the marked reduction in delivered ventilation with either circuit when a humidifier was added. (See text for details.)

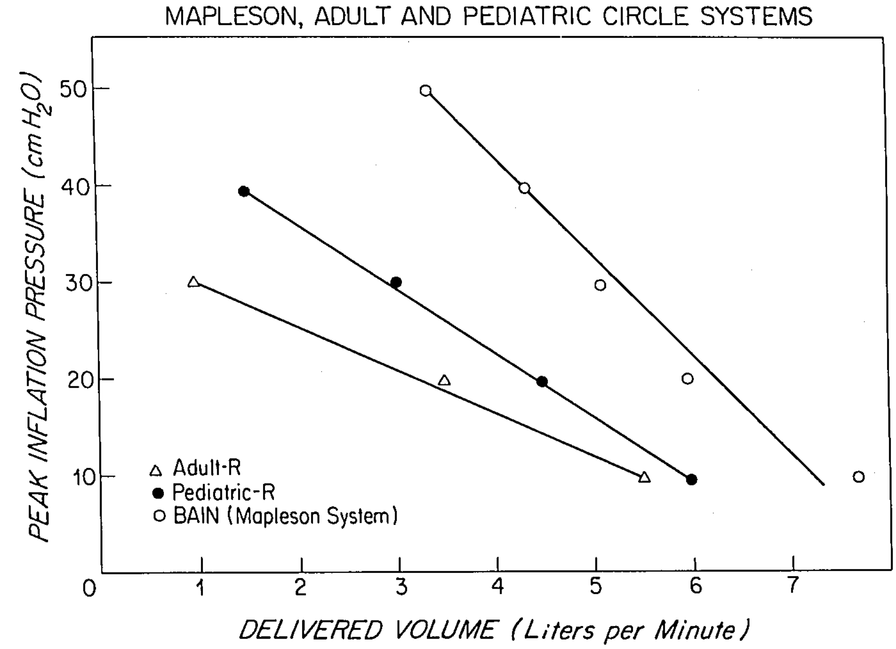

FIG. 3. This figure illustrates the delivered minute ventilation ($\dot{V}E$) with three types of circuits tested with a heated humidifier. All circuits were studied with the same ventilator settings and fresh gas flow. Note that at 30 cm H_2O peak inflation pressure (PIP) there was a fivefold difference in $\dot{V}E$. The adult rubber circuit (R) was so compliant and had such a large compression volume that the entire tidal volume of the pediatric ventilator was contained in the circuit above 30 cm H_2O PIP. The pediatric rubber circuit (R) was intermediate in function and would perform up to 40 cm H_2O PIP. The Mapleson D circuit (Bain) was the most efficient variety of circuit ($P < 0.0001$).

ation, the volume of the circuit is very important, while in the latter, the circuit material.[12]

In clinical situations we have observed serious miscalculations in delivered $\dot{V}E$ due to a large compression volume, which could be directly attributed to the volume of the anesthetic circuit and the compliant circuit material. The increased use of disposable plastic circuits and heated humidifiers obligates an awareness of what influence circuit volume and material might have on efficiency of performance; this is particularly important when caring for infants where the tidal volume is small but the volume and compliance of the circuit large.

The Mapleson D circuits with humidifier had the smallest compression volumes and more efficient circuit function, compared with all circle systems. The pediatric circle systems demonstrated larger compression volumes, while the adult plastic and rubber circuits had the greatest compression volumes. Both the volume of the circuit and the material of which it was constructed were important determinants of compression volume and therefore circuit efficiency. The addition of a humidifier to any circle system increased the compression volume and therefore decreased circuit efficiency. This effect was more pronounced with the pediatric circle systems (Table 3; Fig. 2) probably because the addition of a humidifier proportionally increased the volume of these circuits to a greater extent than adult circuits. Some circuits, particularly with a humidifier, had such large compression volumes that the entire tidal volume of the pediatric ventilator was lost (table 2). The use of a humidifier as a means of maintaining patient temperature therefore must be accompanied by an awareness of what effect this added circuit volume will have on circuit function. Figure 1 presents the compression vol/cm water PIP, while figure 3 demonstrates that there may be as much as a fivefold difference in delivered minute ventilation, despite identical ventilator settings and fresh gas flow.

Circuit material also appears to be an important determinant of circuit function. This factor was demonstrated clearly when comparing the adult wire reinforced circuit to the adult rubber circuit. At 30 cmH_2O PIP, the ventilation losses of the rubber circuit were about twice that of the wire reinforced circuit. When using a pediatric ventilator with the adult rubber circle system, the entire tidal volume was taken up by the compression volume of the rubber circuit whenever PIP exceeded 30 cmH_2O. The wire-reinforced circuit, however, could function up to 50 cmH_2O PIP, whereas the plastic circuit was intermediate (table 2).

Although it is often difficult to extrapolate *in vitro* data to *in vivo* situations, the clinical implications of this study are important. Humidifiers should be used with any nonrebreathing system in order to help maintain temperature and prevent drying of secretions and potential mucus plug formation. Their use in this circumstance did not contribute significantly to compression volume, because these circuits had the smallest compression volume and were the most efficient. The use of humidifiers with pediatric circle systems is also a very useful means for preserving body heat, however, this must be accompanied by an increase in tidal volume and minute ventilation in order to compensate for the increased compression volume. Although adult circle systems have been used successfully in small children during spontaneous ventilation, the large compression volume, especially with a humidifier, make them potentially dangerous with the use of controlled ventilation.[13] Less compliant systems (wire reinforced) may be more advantageous, because compression volume losses are more similar to pediatric circle systems.

We conclude: 1) the anesthetic circuit, the material of which it is constructed, and the pressure at which it must operate are important determinants of circuit function; 2) humidifiers increase compression volume and reduce the efficiency of circuit function; 3) Mapleson D circuits had the smallest compression volume and performed more efficiently than the circle systems; 4) the use of highly compliant adult circuits in pediatric cases may result in compression volume losses that may exceed the tidal volume delivered by a pediatric ventilator; 5) when humidifiers are used, a low-volume humidifier with rigid tubing should have the least effect on circuit function; 6) If adult circuits must be used in the care of infants and small children, especially with controlled ventilation, then some means of assessing the adequacy of ventilation (blood gas analysis, end-tidal CO_2, transcutaneous CO_2) is suggested, this is in addition to careful clinical evaluation of the patient (chest movement, breath sounds, respiratory rate, peak inflation pressure).

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