The Effects of Inflow, Overflow and Valve Placement on Economy of the Circle System

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Several arrangements of inspiratory and expiratory valves and of overflow location in a circle absorber system were tested to determine which arrangement best conserved fresh gas and preferentially eliminated alveolar gas. The influences of inflow rate, deadspace, tidal volume and alveolar ventilation were also examined. During spontaneous ventilation, the most economical arrangements (most alveolar gas eliminated at a given inflow rate) were those with the overflow close to the patient. However, with one exception, when ventilation was controlled, the arrangements with overflow near the patient became least economical. The exception was the arrangement with both inspiratory and expiratory valves close to the patient and the overflow valve immediately downstream from the expiratory valve. This proved to be the most economical of all the arrangements tested. Economy was directly related to inflow rate and indirectly related to alveolar ventilation in all cases. When the overflow valve was distant from the patient, concomitant increases in deadspace and tidal volume (alveolar ventilation unchanged) reduced economy. However, these increases of deadspace and tidal volume had no effect on economy when the overflow was close to the patient.

The designs of most circle absorption systems do not provide for maximal economy in the use of soda lime or anesthetic gases. Brown et al. evaluated the influence of the relative location of inspiratory inflow, overflow (pop-off) and inspiratory and expiratory valves on rate of utilization of soda lime. They found that expenditure of soda lime was slowest when the valves were nearest the patient, with the in-

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Fig. 1. Illustration of the model used to simulate the "lung." The "lung" was connected through the deadspace to the circle system. The construction allowed the CO₂ containing deadspace gas to be drawn on inspiration into the "lung." This was followed by fresh inspired gas from the system. 200 ml./min. CO₂ was added to these gases. These well-mixed gases were then exhaled, pushing ahead of them the non-CO₂ containing gas present in the deadspace.

flow between absorber and inspiratory valve and the overflow between expiratory valve and patient. However, these studies were done at constant inflow, ventilation and subject's deadspace. We have extended Brown's work using a different technique. We have evaluated several circle system designs and have investigated the effects of variations in inflow rate, ventilation and deadspace on the conservation of soda lime and anesthetic gases. Finally, we have examined the reasons for the differences in function found with the various designs.

Methods

A simulated "lung" (fig. 1) was constructed from a leak-proof Harvard Respiration Pump connected to noncompliant tubing. Valves placed at the opening to the "lung" assured unidirectional flow. The Harvard pump delivered a sine-wave ventilatory flow pattern and allowed control of tidal volume and frequency. An inflow of 200 ml./min. of CO₂ through a calibrated flowmeter simulated CO₂
production. Complete mixing of CO₂ with the
gases ventilating the “lung” was evidenced by
a smooth plateau of end-tidal CO₂ concentra-
tion (F_{ACO₂}) measured with an infrared CO₂
analyzer. “End-tidal” samples were taken from
the midpoint or “lung” end of the deadspace
which was interposed between “lung” and
circle system.

The various circle-system arrangements were
divided into three groups distinguishable by
the positions of inflow and inspiratory and ex-
spiratory valves (figs. 2, 3, 4). Group subdivi-
sions were made by placement of the over-
flow. A calibrated rotometer delivered oxygen
at inflow rates of 1.04, 2.04, 4.13, 6.13, 8.25
and 10.26 liters per minute (L/min.). A three-
liter reservoir bag was used. The spring-loaded
overflow valve (located at A through H)
opened at 1 to 3 cm. of water pressure. Gases
exiting through this valve were collected into
and directed through a long length of wide-
bore tubing. We measured the CO₂ con-
centration of these gases (F_{EFCO₂}) at the point
closest to the overflow valve where no fluctua-
tion of F_{EFCO₂} could be found: that is, we
measured the mean CO₂ concentration in the
effluent. The volume of gas exiting per minute
(V_{EF}) was calculated as 1.03 V_{IX}/(1-F_{EFCO₂}).
1.03 was a correction for added water vapor
at 20° C. and 1-F_{EFCO₂} was a correction for
CO₂ not absorbed. Both were small corre-
tions. V_{EF} also equals the sum of gas input
per minute into the system. We calculated
the overflow of CO₂ per minute (V_{EFCO₂}) as
V_{EF}·F_{EFCO₂}. The per cent of total CO₂ pro-
duction eliminated in the effluent (i.e., 100
V_{EFCO₂}/0.2 L/min.) gave the economy of the
arrangement studied. This was the figure co-
dordinate “per cent CO₂ eliminated through
overflow.” The closer this approached 100
per cent, the more economical the arrangement.

All arrangements (A through H) were first tested at an $F_{ACO_2}$ of 0.06 (i.e., 6 per cent CO$_2$), with a deadspace of 150 ml. and a tidal volume of 300 ml. In a second experiment, deadspace and tidal volume of arrangements C, D, F and H were increased concomitantly in three steps of 100 ml. each. Since there was no change in alveolar ventilation, $F_{ACO_2}$ remained at 0.06. In a third experiment with C, D, F and H, deadspace and tidal volume were held at 150 ml. and 300 ml., respectively, while respiratory frequency was adjusted to produce $F_{ACO_2}$ values of 0.03, 0.06 and 0.1 (3, 6 and 10 per cent CO$_2$).

In all the above experiments ventilation was spontaneous. In a fourth experiment a ventilator replaced the circle-system reservoir bag and a rubber bag replaced the Harvard pump in the "lung." The pressure from the ventilator was adjusted to produce $F_{ACO_2}$ of 0.06. Deadspace (150 ml.) and respiratory frequency equaled values used in the first group of studies.

To evaluate the conservation of fresh anesthetic gases, the "lung" was modified so that inspired gas containing CO$_2$ ($F_{INSPIR}$) was directed either through a CO$_2$ absorber or through a variable orifice tube bypassing the absorber (fig. 5). By adjustment of the orifice, the desired uptake (removal) of CO$_2$ could be achieved. That is, "exhaled" or "end-tidal" gas ($F_{ET}$) might contain anything from 0 to 100 per cent of the inspired CO$_2$. Uptake could thus be made to resemble that commonly occurring with any agent. For example, removal of 50 per cent of the inspired CO$_2$ ($F_{ET}/F_{INSPIR} = 0.5$) simulated halothane uptake, and 80 per cent removal ($F_{ET}/F_{INSPIR} = 0.2$) simulated methoxyflurane or ether uptake.

The circle system was also modified. The CO$_2$ absorber was removed, and CO$_2$ was added to the inflow to give a concentration of 12 per cent or less ($F_{INFL}$). Total volume inflowing was calculated as the inflowing O$_2$ plus any CO$_2$ that was not "taken up." Arrangements A, F and H were thus tested with a deadspace of 150 ml., a tidal volume of 300 ml. and the same frequency as used in the first study (i.e., the same characteristics which had produced an $F_{ACO_2}$ of 0.06). The economy of the system was defined in terms of the closeness with which the inspired concentration of CO$_2$ approached that in the inflowing gas. That is, the closer $F_{INSPIR}/F_{INFL}$ approached 1.0, for any given inflow rate and uptake, the more economical the system.

Results

In all cases where ventilation was spontaneous, an increase in inflow increased economy of CO$_2$ elimination although, of course, not of anesthetic gas utilization. However, at any particular inflow, the economy achieved by a system varied markedly with valve and inflow placement (figs. 2, 3, 4). In general, economy was greatest in those arrangements having the overflow near the patient (B, D, H and G, fig. 6). With concomitant equal increases in deadspace and tidal volume, economy was unchanged when overflow was near the patient (figs. 7, 8, D and H), but decreased when overflow was distant from the patient (C and F). As alveolar ventilation increased, system economy decreased regardless of overflow placement (figs. 9, 10).

With change from spontaneous to controlled ventilation, economics of arrangements B, D and G went to zero. That is, no CO$_2$ exited through the overflow, all being directed through the absorber. The remaining arrange-
Fig. 6. The lines drawn visually through the data points illustrated in figures 2, 3 and 4 have been combined to make this figure. This allows a comparison of the economy of the various arrangements.

Arrangements A, C, E, F and H retained the economy they demonstrated at comparable deadspace, frequency and $F_{ACO_2}$. This is illustrated for arrangements A, F and H in figure 11.

When uptake removed 50 or 80 per cent of the gas reaching the alveoli, system A was least economical of anesthetic gas, H most economical and F intermediate. There was a large relative difference between arrangements (figs. 12, 13) at low inflow rates. For example, at 80 per cent uptake and a 2-liter-per-minute inflow, $F_{INSV}/F_{INFL}$ equaled 0.48 for A and 0.66 for H, a 37 per cent increase (fig. 13). At an inflow of 10 liters per minute, H was only 5 per cent greater than A.

Discussion

The object of any arrangement which seeks greater economy is the conservation of those gases which have not reached the alveoli, and the ejection of those which have. At any given inflow rate, the most economical system tends to retain those gases containing the greatest concentration of anesthetic agent and the lowest concentration of CO$_2$. Anything which lowers the CO$_2$ concentration in the overflowing gas reduces economy, anything which raises the concentration improves economy. In this context we have found large variations between the economies of the various systems. The following discussion gives a qualitative explanation to these variations.

System B is a more economical arrangement than A (fig. 2). The gases reaching A are composed of inflowing gas (no CO$_2$), deadspace gas (no CO$_2$), and alveolar gas (6 per cent CO$_2$). Since deadspace (150 ml.) makes up half the tidal volume (300 ml.), the concentration of CO$_2$ in the existing gas ($F_{ECO_2}$) must be half or less than half of the alveolar concentration ($F_{ACO_2}$). This is not the case with arrangement B. At the end of inspiration, the reservoir bag is partially collapsed.

Fig. 7. This illustrates the relative economies of arrangements C and D with concomitant and equal increases in deadspace and tidal volume. Since increase in tidal volume was matched by increase in deadspace, alveolar ventilation and $F_{ACO_2}$ remained unchanged.

Fig. 8. This illustrates the relative economies of arrangements F and H with concomitant and equal increases in deadspace and tidal volume. Since increase in tidal volume was matched by increase in deadspace, alveolar ventilation and $F_{ACO_2}$ remained unchanged.
and the pressure within the system is essentially zero. As expiration proceeds, the bag fills with gas both from the lung and from the inflow. The gas which leaves the "lung" during the first part of expiration is deadspace gas (no CO₂), and since the overflow valve is not open during this time, this gas is conserved. When the reservoir bag is filled, the pressure in the system rises sufficiently to open the overflow valve. Since opening occurs during the latter part of expiration, gases expelled contain more or less alveolar gas, depending on the inflow rate: the higher the inflow rate, the lower the FₑF₈CO₂. At a low inflow rate

the FₑF₈CO₂ approaches FₐCO₂ (6 per cent), and in this case B may be almost twice as economical as A.

A similar explanation may be given for the greater economy of arrangements having the overflow at the patient (D, G and H) as opposed to those having the overflow away from the patient (C, E and F). With the overflow at the patient, deadspace gas tends to be retained within the system and alveolar gas expelled. No such discrimination is possible when the overflow is distant from the patient.

C is a more economical arrangement than E (fig. 3) because gases exiting at E contain deadspace gas, alveolar gas and inflow gas, whereas gases expelled at C need only contain deadspace and alveolar gas. With C the only gases traveling down the expiratory tubing are those exhaled by the patient. During expiration the inspiratory valve is closed, and the inflowing gas must flow "backwards" through the cannister and into the reservoir bag or towards the overflow valve. The inflow drives before it gas previously exhaled by the patient. Inflowing gas itself is expelled through the overflow only when inflow exceeds the minute ventilation of the patient.* Until inflow exceeds minute ventilation, the only gases expelled are those expired. Since expired gases have a constant mixed CO₂ concentration, the per cent CO₂ eliminated through the overflow is rectilinearly related to

*Actually this is exactly true only if there is "plug flow" rather than "cone flow" of the inflowing gas.

**Fig. 9.** While deadspace and tidal volume were held at 0.15 and 0.3 L, respectively, respiratory frequency was adjusted to produce FₐCO₂ values of 0.03, 0.08 and 0.1. This illustrates the effect of such changes on the economics of arrangements C and D.

**Fig. 10.** While deadspace and tidal volume were held at 0.15 and 0.3 L, respectively, respiratory frequency was adjusted to produce FₐCO₂ values of 0.03, 0.08 and 0.1. This illustrates the effect of such changes on the economics of arrangements F and H.

**Fig. 11.** In the previous figures ventilation was spontaneous. This figure illustrates the lack of change in economy for arrangements A, F and H when ventilation was controlled but tidal volume, deadspace and FₐCO₂ were unchanged.
inflow rate (i.e., the graph for C in figure 3 is a straight line). This reasoning also applies to arrangement F and thus the economies of C and F are identical (fig. 6). Arrangement E is less economical than either C or F, since inflow cannot flow backwards once the reservoir bag has filled and gas is being expelled through the overflow. This is because the expiratory valve lies between inflow and overflow; thus, after the reservoir bag has filled, the inflowing gas must move forward around the circle, joining and diluting the exhaled gas. The fact that flow can go backwards with arrangement E until the reservoir bag is filled also explains why E is more economical than A (fig. 6). With A, inflow must at all times go forward around the circle, diluting the expired gas as it does so. Thus, there is greater dilution of expired gas than with E, where dilution occurs only during the latter part of expiration.

Arrangement H is more economical than G. This results from the preferential elimination of undiluted alveolar gas with H, but dilution of such gas with inflow in the case of C. With H, as expiration proceeds, the reservoir bag fills with flow from lung and backward flow from the inflow. When the bag is full and the overflow valve opens, the alveolar gas being expired by the patient is ejected. In addition, the alveolar gas previously ejected into the expiratory limb of corrugated tubing now is driven back and out the overflow valve by the backward-flowing inflow. Thus, no inflowing gas or deadspace gas is expelled through the overflow until all the alveolar gas is expelled.** Such is not the case with arrangement G, where inflow moves backwards only until the reservoir bag is full and the overflow opens. Inflow must then reverse its direction, pass through the inspiratory valve and out through the overflow. This dilutes the alveolar gas being expelled. As opposed to arrangement H, any alveolar gas which has traveled past the expiratory valve cannot be expelled but must go through the CO₂ absorber. This also explains why, at higher inflow rates, G is less economical than C and F.

It is difficult to explain why D is more economical than G or indeed why D should have the same economy as H (fig. 6). The reasoning that applied to G should apply equally to D, and yet experimentally the two arrangements produced different results. One possi-

** Again assuming plug flow.
bility is that with D a small portion of alveolar gas travels down the inspiratory limb during expiration. This might result from both convection and diffusion. Following opening of the overflow valve, the inflowing gases would not immediately dilute the exiting expired gas, but would sweep before them the CO₂ containing gas which had previously made its way down the inspiratory limb.

Qualitatively, part of our results confirm the work of Brown. During spontaneous ventilation, the arrangements with overflow near the patient (B, D, G and H) are the most economical at any given inflow rate (figs. 2, 3, 4). With the exception of H, the economy of these arrangements approaches zero when ventilation is controlled, whereas the economy of the remaining arrangements remains unaffected (fig. 11). Our results sometimes differ considerably from those of Brown. For example, during spontaneous breathing Brown finds that C is two to three times more economical than B. We also find C more economical than B at inflows exceeding 5 l/min., but at inflows less than this the reverse is true; B becoming more economical than C. Similarly, Brown finds G is the most economical of all arrangements during spontaneous breathing, whereas we find G is the most economical (along with D and H) only at inflows less than 1.5 l/min. Above an inflow of 3.4 l/min., it becomes less economical than B, C and F (fig. 6).

Increase in deadspace without change in alveolar ventilation has no effect on the economy of overflow positions at the patient (D and H, figs. 7, 8) but reduces economy of those away from the patient (C and F). This may be explained as follows. Gas in the expiratory limb of C and F is composed of deadspace gas (no CO₂) and alveolar gas (6 percent CO₂). With increase in deadspace gas relative to alveolar gas, there is a decrease in F_{EFCO₂} and consequently a decrease in economy. With arrangements D and H the deadspace gas is conserved. The increase in volume of deadspace does not affect economy. Put another way, regardless of deadspace increase, the overflow valve opens where the same volume of gas remains to be exhaled. Thus the same amount of alveolar gas escapes through the overflow.

Economy of all systems decreases when alveolar ventilation is increased (figs. 9, 10). Conversely, economy increases with hypoventilation. This follows from the change in F_{ACO₂}. With arrangements C and F, F_{ACO₂} and F_{EFCO₂} must rise together, because F_{EFCO₂} is produced from the mixture of deadspace and alveolar gas and because the relative volumes of deadspace and tidal air remain constant. Similarly, with arrangements D and H, F_{EFCO₂} is a direct function of F_{ACO₂}, which is preferentially eliminated with these arrangements. Since economy is directly related to F_{EFCO₂}, economy must decrease as alveolar ventilation increases.

The results we obtained are probably dependent in some cases on the pattern of breathing. In this study we chose a sine wave since we have found this to be most representative of ventilation in the anesthetized patient. If there is a prolonged pause at end inspiration, systems B, E, G and D should become more economical. A greater portion of inflow gas in these cases would be used to fill the reservoir bag before expiration and a lesser portion would contribute to the dilution of alveolar gases exiting through the overflow. We suspect that the economy of the remaining arrangements would be unaffected, since inflow does not contribute to dilution of effluent gases until high inflow rates are used. Conversely, if the breathing cycle consisted of rapid inspiration immediately followed by rapid expiration followed by an expiratory pause occupying most of the cycle time, then systems B, E, G and perhaps D should become less economical. In this case inspired gas would be drawn almost entirely from the reservoir bag which would be immediately refilled by expiration. The overflow would be open during only a small fraction of the inspiratory-expiratory movement, since there would be no change in system plus lung volume and hence no excess gas to eject. During the end-expiratory pause the inflow gas would force fresh gas out the overflow (B, D and G) or down the expiratory limb (E). F_{EFCO₂} would therefore be near zero (B, D and G) or lowered from that obtained with the sine wave pattern (E).

Controlled respiration (fig. 11) either produces no change in economy (A, G, E, F
and H) or reduces economy to zero (B, D and G). Those arrangements which lose economy have the overflow at the patient without interfering the expiratory valve between patient and overflow. Since gas ejection from the system (overflow valve opening) occurs during inspiration, the gas ejected in B, D and G must be fresh gas. CO₂-containing gas is retained and economy equals zero.

Factors influencing CO₂ removal should play similar roles in conservation of fresh anesthetic gas. Thus if deadspace and tidal volume increase while alveolar ventilation remains constant (FACO₂ constant), we would expect that fresh gas conservation would be unchanged with system H while it would decrease with A and F.

Under all conditions tested, H is the most economical of all arrangements. In addition, it produces the most predictable inspired anesthetic concentrations. However, against these virtues must be balanced the defects inherent in the commercially-available H arrangement. These are: (1) it is somewhat bulky and slightly heavier than the simple Y piece; (2) the valves are more difficult to see than dome valves; (3) the valves may "stick" on first use after a period of non-use. Opening these valves at this time may require considerable pressure; (4) resistance to flow may be slightly greater than the resistance in dome valves; (5) flushing with oxygen does not clear the inspiratory limb since inflow gases flow backwards.

Arrangement D is as economical as H when breathing is spontaneous and is sine-wave in form. However, economy goes to zero when ventilation is controlled. This loss of economy is prevented by changing the overflow valve from a spring-loaded valve to a Steen type which closes with rapid rises in system pressure (i.e., closes on inspiration) (unpublished data). With this alteration D becomes as economical as H without having some of the disadvantages listed above. It is still more cumbersome than a simple Y piece.

Summary

We examined the economy of several arrangements of inflow, overflow and inspiratory and expiratory valves. Greatest economy (greatest percentage of alveolar gas eliminated through the overflow) was obtained during spontaneous breathing when the overflow valve was placed near the patient. Lowest economy occurred when the overflow was distant from the patient. Increasing deadspace and tidal volume so as to maintain alveolar ventilation constant caused no change in economy when overflow was near the patient, but caused a directly related decrease in the economy of those arrangements with overflow distant from the patient. Increasing alveolar ventilation decreased economy in all arrangements. Change in ventilation from spontaneous to controlled resulted in no change in economy of arrangements with overflow distant from the patient, but with one exception reduced to zero economy those arrangements with overflow near the patient. The exception was the most economical arrangement under all circumstances. This arrangement placed inspiratory and expiratory valves at the Y piece connection to the patient. The overflow was immediately downstream from the expiratory valve.

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Reference