Closed circuit anesthesia:
A practical alternative

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Closed circuit anesthesia has begun to resurface as a useful and applicable method of anesthesia delivery. This article describes the method for use of closed circuit anesthesia without the necessity of a nitrous oxide supply system. This system of closed circuit delivery is used at the authors' hospital and is easily adaptable for use in other clinical settings.

The use of closed system anesthesia in humans had its beginnings with Dr. John Snow, who used chloroform in a closed system with potassium hydroxide as a carbon dioxide absorber as early as 1850. In that same year, Coleman developed a closed system using calcium hydroxide as a carbon dioxide absorber and with it delivered more than 100 anesthetics. The system was bulky and inconvenient to use which did not help its popularity. In 1917, a breakthrough occurred due to the need for an efficient filtering system for gas masks during World War I. In that year, Wilson and others developed 4 to 8 mesh soda lime pellets which are used today for carbon dioxide absorption. In 1926, Ralph Waters developed the Waters Carbon Dioxide Filtration System. Called the "to and fro system," it was simple, less bulky and according to Lowe, could be safely used today if an O2 analyzer were added to the reservoir.

In 1933, cyclopropane, an explosive agent, was discovered, which necessitated the use of closed systems for its safe delivery. From the 1930s until the late 1950s, closed system anesthesia was the most popular way to deliver inhalation anesthesia. The discovery of halothane in 1956 resulted in a decreased use of flammable and explosive anesthetics. Closed system anesthesia lost its popularity and is a rarely used method of anesthesia delivery today. However, the technique is being revived as evidenced by the establishment of the Closed and Lowflow Anesthesia Systems Society (CLASS).*

In 1973, Weingarten and Lowe described a technique for injection of liquid anesthetic into the exhalation limb of the breathing circuit. Although described for methoxyflurane and the other inhalation agents, it is the delivery system which is utilized at the authors' hospital for closed circuit anesthesia. In 1970, the concept of providing the cumulative dose equivalent to the area under the uptake curve on a weight basis evolved. It led to the development of the square root of time model for the uptake and distribution of volatile agents.

In this model, Lowe developed the exponential saturation equation which predicts equal rate of whole body uptake determined at 4, 9, 16, 25, etc. minutes. Simply stated, to maintain a constant blood level, the amount of anesthetic removed by the blood from the alveoli during the 4th to the 9th minute is equal to the amount removed during the 9th to the 16th minute. The alveolar concent-

*Closed and Lowflow Anesthesia Systems Society, P.O. Box 338 JCRS, 6677 W. Colfax Ave., Denver, CO 80214-1896.
tration is assumed to be replenished and therefore remains constant. It should be noted that the interval between squares of successive integers increases by two.

<table>
<thead>
<tr>
<th>Integer</th>
<th>Squares</th>
<th>Interval from</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1 to 4 = 3</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>4 to 9 = 5</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>9 to 16 = 7</td>
</tr>
</tbody>
</table>

Therefore, at steady state, the uptake for the same amount of anesthetic is prolonged by two minutes if rate of uptake is determined using squares of consecutive integers as sampling times. The amount taken up during each time interval is referred to as *unit dose*. Similarly, the total cumulative dose is directly proportional to the square root of the duration. Therefore, the number of unit doses is equal to the square root of the duration of anesthesia. Total cumulative dose is the sum of the unit dose plus the prime dose (amount of anesthetic needed to saturate the breathing system at 1.3 MAC of an agent).

In 1942, Brody established the relationship between the weight in kilograms of adult mammals and their basal oxygen requirements. He stated that “oxygen consumption is an exponential function of body weight and when expressed in ml/minute it equals 10 kg$^{3/4}$.” This function becomes an excellent predictor of the patient’s oxygen consumption during basal conditions. By using the Brody number in conjunction with work done by Kleiber and others, the following can be predicted.

1. Minute O₂ use – $\dot{V}O₂ = 10 \text{ kg}^{3/4}$
2. Cardiac output – $Q = 2 \text{ kg}^{3/4}$
3. Fluid requirements – $\text{H}_2\text{O req} = 5 \times \text{ kg}^{3/4}$
4. CO₂ production – $\dot{V}O₂ = 0.8 \times \dot{V}O₂$
5. Alveolar ventilation – $\dot{V}A = 160 \times \text{ kg}^{3/4}$
6. Minute ventilation – $\dot{V} = \dot{V}A + 1/2 \dot{V}A$
7. Body surface area – BSA = .08 × kg$^{3/4}$
8. Brody’s number – kg$^{3/4} = \text{kg} \times \text{kg} \times \text{kg} = \sqrt[3]{\text{kg}^3}$

It is necessary to be able to mathematically determine these values for each patient prior to the delivery of anesthetic through a closed circuit system. It is also necessary to determine the *unit dose*, *prime dose*, and *fresh gas flow rate* for each patient. These will be described later in this article.

**Unit dose.** To determine the amount of anesthetic agent that is injected into the expiratory limb of the system the following formula may be used:

\[
\text{Unit dose} = 2 \times (\text{Ed95}) \times \text{BG} \times \text{patient's cardiac output} = \text{ml vapor}
\]

\[
\text{Ed95} = 1.3 \times \text{MAC}
\]

(Minimum Alveolar Concentration)

Prime dose = Unit dose + 100 (1.3 × MAC)
when 100 dl = volume of circuit

\[
\text{BG} = \text{blood:gas partition coefficient}
\]

This formula determines the amount of vapor needed. To determine the amount of liquid/per unit dose, this number is divided by the amount of vapor which one ml of the agent produces at 37°C.

1 ml halothane = 240 cc vapor
1 ml enflurane = 210 cc vapor
1 ml isoflurane = 206 cc vapor

\[
\begin{align*}
\text{BG} & = 2.4 \text{ MAC} = 0.75 \\
\text{BG} & = 1.9 \text{ MAC} = 1.7 \\
\text{BG} & = 1.3 \text{ MAC} = 1.3
\end{align*}
\]

Unit dose is not an absolute amount. Since individuals react differently, it may be necessary to modify the dose and/or adjust dosing times accordingly. As described by Lowe and others, the unit dose is to be given at the times that correspond to the square of the consecutive integers:

Integers 1, 2, 3, 4, 5, 6, to 14
Anesthesia times 1, 4, 9, 16, 25, 36, to 196

Standardized dosage charts are available in most literature on closed system anesthesia. These are a good guide although the formulas in this article will help determine the needed numbers for each case.

**Equipment.** When the pop-off valve is closed down so that there is minimal or no leakage from the circle system, existing anesthesia delivery systems in use today can be utilized. However, some modifications may be necessary in order to provide the most optimal system. These include:

1. Flow meters must be accurate to 25 ml/minute of oxygen delivery.
2. The system must be free of low pressure leaks which can cause entraining of ambient air during the negative pressure portion of the respiratory cycle. This leads to dilutional effects on the
anesthetic concentration in the system and inaccurate determination of VO₂. Leaks during the inspiratory cycle will decrease the delivered amount of gas to the patient.

3. Oxygen monitors are mandatory in order to insure delivery of nonhypoxic gas mixtures to the patient when nitrous oxide is used during closed system anesthesia.

4. It is preferred that an upright bellows ventilator be used in lieu of a descending inverted bellows ventilator. It decreases the possibility of air leaks secondary to sustained negative end expiratory pressure.

5. One item which is not standardized but must be individualized to each institution is a template marked off in squares which corresponds to actual minutes of anesthesia time, that is, 1 minute, 4 minutes, 9 minutes, and so on. This template is matched to the local anesthesia record for ease of administration of liquid anesthetic into the system. A device as simple as a tongue blade can be used for this purpose (Figures 1 and 2).

6. A stop watch or watch with a sweep hand is also used to count actual anesthesia time.

7. Standardized dosage charts are available in most literature on closed circuit anesthesia, obviating the need to calculate the doses. There are many listed in the references to this article.

Anesthetic System: Expiratory Limb Fluid Injection Method. A disposable circle system is most appropriate because less anesthetic is absorbed in the plastic compared to the conductive neoprene rubber. A 25-gauge spinal needle or a 25-gauge scalp vein needle (use caution, because plastics tend to dissolve in isoflurane) is inserted into the expiratory limb close to the CO₂ canister (Figure 3). Care should be taken to minimize the size of the hole and prevent it from enlarging. A layer or two of adhesive tape around the breathing tube where the needle would enter prevents the hole from enlarging and minimizes gas leaks.

It is important to prevent back pressure into the syringe, and a 25-gauge spinal or scalp needle is ideal for this. Also a 10 ml plastic disposable syringe is better than a glass syringe, as back pressure tends to push out the plunger in glass syringes. A stopcock can be utilized to prevent an accidental bolus injection of liquid anesthetic agent. The syringe is labeled so as to prevent accidental intravenous injection which could have dangerous results. It is advised that the syringe be filled with 10 ml of liquid anesthetic initially and with each refill, for the ease of determining total cumulative dose (difference between initial volume and the volume that remains in the syringe). (Figures 4 and 5.) This method, utilized in the authors' anesthesia department, is inexpensive, easy and requires very little preparation time.

For most ASA 1 and 2 patients, anesthesia is induced with sodium thiopental after a defasciculating dose of d-Tubocurarine is administered and intubation is facilitated with the use of succinyl-

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Figure 1
Example of template

<table>
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<tr>
<th>1</th>
<th>16</th>
<th>36</th>
<th>39</th>
<th>49</th>
<th>64</th>
<th>81</th>
<th>100</th>
<th>121</th>
<th>144</th>
<th>169</th>
<th>196</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Minutes of Anesthesia)</td>
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</table>

Figure 2
Example of homemade template with formulas for closed circuit anesthesia

Figure 3
25 gauge spinal needle being inserted into plastic tubing to deliver liquid anesthetic
choline. To prevent marked cardiovascular response to laryngoscopy and tracheal intubation, a heavier dose of sodium thiopental may be required, such as 7-10 mg/kg, or alternatively a sleep dose of thiopental and 2 μg/kg of fentanyl may be used for induction. Preoxygenation can be accomplished by keeping the system open prior to intubation, with the use of 100% O₂, followed with a rapid sequence intubation. Immediately after intubation the system is closed and the prime dose plus the one minute dose is given. The patient may be hand ventilated while the practitioner also checks for breath sounds, before switching the patient to mechanical ventilation.

Liquid isoflurane is injected into the expiratory limb of the circuit as described earlier at predetermined dosing times which are the squares of each consecutive whole number. It has been found that the anesthetic course for the patient tends to be more stable when fractions of the unit doses are given as required by the patient rather than in full unit doses at predetermined times. The anesthetic requirement will vary due to levels of surgical stimulation during the surgical procedure and will also vary among individual patients. In any case, fractional doses narrow the peaks and valleys in vital signs and depth of anesthesia.

Emergence. When the surgical procedure is nearing completion, it becomes necessary to decide when to stop the anesthesia and begin the “waking up” process. With closed system anesthesia, this wake up time can be determined with remarkable accuracy by using another aspect of the square root of time model. A certain amount of anesthesia time at 1:3 MAC is ensured for each unit dose. Each unit dose will decay exponentially depending on the length of anesthesia. The decay may be referred to as coasting time, defined as the time required for the cumulative effect of anesthesia to decrease from 1.3 MAC to 1.0 MAC or less. Mathematically, coasting time equals 2 times the square root of the duration of anesthesia plus one minute.

For example, when the last dose is given at 144 minutes, 25 minutes (2 times the square root of 144 plus 1 minute) of coasting time is available for anesthesia. When it becomes necessary to provide a few more minutes of anesthesia time to finish the surgical procedure, a partial dose of anesthesia (1/4 to 1/6) will provide the additional time without increasing emergence time to the degree of a full unit dose. If desired, coasting time may be shortened by increasing the flow and opening the system. An alternative method to also shorten coasting time is to place an activated charcoal filter in a closed system to prevent rebreathing of the anesthetic vapor.

Case study

Mrs. F, a 38 year old white female, was admitted to the hospital for an elective bilateral mammoplasty. Her previous medical history was unremarkable with the exception of a 2 year history of hypertension, treated with hydrochlorothiazide and clonidine (Catapres®). Her blood pressure on admission was 120/80 in the right arm without significant change in the left. Her past
surgical history included appendectomy, bilateral oopherectomy and total abdominal hysterectomy, performed under general anesthesia. All anesthetics were without incidence. Preoperatively all laboratory data, and chest x-ray were within normal limits. Physically she was 70" tall and weighed 74 kg. Preoperative medication was with clonidine 0.2 mg P.O. at 10:00 p.m. the evening prior to surgery.

These values were needed to determine ventilator settings, unit dose of anesthetic and fluid management of this patient.

**Determined values**

Brody's function: $kg^{3/4} = 25.2$

\[ CO = 2kg^{3/4} = 50.4 \text{ dl/min} \]

\[ \dot{V}A = 160 \times kg^{3/4} = 4032 \text{ ml/min} \]

\[ H_2O \text{ Req} = 5 \times kg^{3/4} = 126 \text{ ml/min} \]

\[ \dot{V}O_2 = 10kg^{3/4} = 252 \text{ ml/min} \]

\[ MV = \dot{V}A + 1/2 \dot{V}A = 6048 \text{ ml/min} \]

Unit dose = 2 x $Ed95 \times BG \times CO$ = cc of isoflurane vapor

\[ = x (1.3 \times 1.3) \times 1.3 \times 50.4 = 221.4 \text{ ml of vapor} \]

\[ = 221.4 \div 206 = 1.07 \text{ ml of liquid isoflurane} \]

Mrs. F was transported to the operating room holding area where a 16-gauge intracath was placed in a right arm vein and an infusion of 1 liter lactated Ringer's solution was started at a rate of 125 cc/hour. After transfer to the operating room, EKG monitor, blood pressure cuff and precordial stethoscope were applied prior to induction. The patient was preoxygenated with the system open on 100% $O_2$. A defasciculation dose of 3 mg d-Tubocurarine was given prior to induction which was accomplished with an injection of 500 mg sodium thiopental followed by 120 mg succinylcholine. Intubation was performed without difficulty followed by closing of the system and injection of the prime dose and the 1 and 4 minute unit doses—a total of 3.6 ml of isoflurane into the expiratory limb of the closed system. At 6 minutes an additional unit dose of 1.1 ml was instilled into the system when movement of the patient's head was noted. At 9 minutes the last full unit dose of 1.1 ml was injected into the system.

From minute 9 until minute 169, divided doses of isoflurane which equaled 0.6 ml (unit dose/2) were given in order to provide a more stable course for the patient. These were given when systolic blood pressure was above 130 torr, the heart rate was above 110 beats per minute, or when movement was noted. At minute 83 the patient moved, requiring a unit dose of 1.1 ml.

To provide a comfortable recovery period and to decrease the required amount of isoflurane, fentanyl 50 $\mu g$ was given IV at minute 121 and prior to the end of surgery at 180 minutes. The last partial unit dose, 0.6ml, was given at minute 196. The patient was extubated at minute 225 which was within the predicted emergence time of 29 minutes. The patient was transferred to the recovery room and had an uneventful recovery. The total dose of isoflurane used was 17.0 ml as compared to 16.38 predicted for 196 minutes, that is: 14 doses + prime dose = $14 \times 1.07 + 1.4 \text{ ml} = 16.38 \text{ ml}$.

**Discussion**

Closed system and low flow techniques are excellent methods of anesthesia. In the authors' clinic, closed system anesthesia is most frequently utilized as a model of uptake and distribution. For those who are willing to try this method, it would be wise to note that the predicted oxygen consumption, ventilator setting based on $CO_2$ production and predicted unit doses come very close to the actual values. The authors prefer to use the upright ventilator, because small positive pressure due to the weight of the bellows acts as a very mild form of PEEP. Conversely the weight of the inverted bellows may give a form of NEEP, especially if there is a small leak.

As with all anesthesia methods, absolute vigilance must be exercised with closed system anesthesia. Its advantages include: (1) economy, (2) decreased vapor to scavenge (3) retention of body heat, (4) excellent humidification, (5) simplicity, because there is no requirement for vaporizers or flow meters to keep the bag three-quarters full, and (6) when anesthesia is required in a field situation as in rescue or military operations, this technique can minimize the problems of gas and anesthetic supply and maintenance of the machines. Its use may become more widespread in the future as its advantages become more well known.

**REFERENCES**


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