Chapter 8

CLOSED-CIRCUIT ANESTHESIA

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INTRODUCTION

The military anesthesia provider may be required to provide many hours of care in battlefield medical treatment facilities while working under restrictions that make the usual peacetime practice of anesthesiology infeasible:

- Supplies of compressed gas may be very limited in the field.
- Most ventilators in the inventory are oxygen powered.
- Nitrous oxide, the most commonly used anesthetic during peacetime and in civilian hospitals, has been removed from the U.S. military field inventory.

With oxygen at a premium, the anesthesia provider may need to "squeeze the bag," (ie, to provide manual positive-pressure ventilation) sometimes for many hours, when controlled ventilation is required. Two anesthetic options may aid the anesthesia provider in these circumstances: (1) regional anesthesia and (2) spontaneous ventilation under general anesthesia. Where appropriate to the injury, regional anesthetic techniques, such as brachial plexus blockade and spinal anesthesia, which use a minimum of supplies, can be used. With certain caveats, draw-over vaporizers can provide anesthesia with no compressed gas at all.[1] Because ether is a respiratory stimulant, its use with spontaneous ventilation in a draw-over system does not require oxygen supplementation. Potent volatile agents, such as halothane and isoflurane, are respiratory depressants; therefore, supplementation with at least 1 L/min of oxygen is required during spontaneous ventilation. If these agents are utilized with only air, ventilation should be controlled. The anesthetist must squeeze the bag constantly, because on room air the patient has little reserve during even short periods of apnea. Providing manual ventilation for many hours with a draw-over system's self-inflating reservoir bag can be very uncomfortable.[2] Intravenous anesthetics, such as ketamine, opioids, benzodiazepines, and muscle relaxants can be utilized; however, their use often mandates controlled ventilation.

Two field anesthesia machines are available for deployment with the U.S. Army Medical Department: the Field Anesthesia Machine (FAM) Model 885A and the Ohmeda Universal Portable Anesthesia Circuit (PAC, both manufactured by Ohmeda, Inc., Madison, Wis.) draw-over system (see Chapter 2, Combat Anesthesia Overview and Chapter 7, Military Anesthesia Machines). The FAM 885A is a circle system; the PAC is a nonrebreathing system. A circle system is a closed circuit of gases from which the patient is breathing. These gases consist of oxygen, water vapor, carbon dioxide, sometimes nitrogen, and anesthetic agents, and are confined within breathing tubes with one-way valves, a reservoir bag, a fresh-gas inlet, a pop-off device (ie, an adjustable positive-pressure relief valve), and a carbon dioxide absorption canister, which permits rebreathing of some or all of the exhaled gases. In a closed circuit, the inflow of gases is set to replace only those gases taken up by the patient, in order to maintain the set percentages and volume within the system. A nonrebreathing system, on the other hand, contains only an inspiratory limb of tubing, a reservoir bag, a fresh-gas inflow, and a single nonrebreathing valve between the patient and the system. A nonrebreathing system must supply all of the tidal volume delivered to the patient as fresh gas inflow with each breath. This inflow must contain the appropriate mixture of gases required for anesthesia, as there will be no equilibration between patient and system. The closed-circle system efficiently conserves patient heat, water vapor, anesthetic agent, and oxygen; the nonrebreathing system is smaller and simpler but conserves nothing, as the patient's entire tidal volume is lost to the room or scavenging device.

In its usual semiclosed configuration, the FAM 885A is profligate in its use of compressed gas. However, when low flows are utilized, it can provide a high fraction of inspired oxygen (F_{IO_2}) with very modest expenditure (0.3–0.5 L/min) of compressed oxygen. The compliant reservoir bag is comfortable and controlled ventilation can be provided for many hours without undue fatigue. Additionally, the high F_{IO_2} provides a reserve so that the patient can tolerate short periods of apnea while the anesthetist performs other tasks (eg, hanging a unit of blood for transfusion).

During deployment, with compressed gas at a premium, controlled ventilation will be provided manually. The closed-circuit technique can be used advantageously in two ways: (1) to provide controlled ventilation with a high F_{IO_2} for intravenous techniques and (2) to deliver potent volatile agents by liquid injection for techniques utilizing sponta-

neous or controlled ventilation. Anesthesia personnel deployed with the U.S. Marines during the Persian Gulf War used closed circuit anesthesia with liquid injection of halothane. With high ambient temperatures and limited logistical reserves, the method proved both workable and useful.[3]

OXYGEN AND POSITIVE-PRESSURE VENTILATION

The circle system can be used to provide a high FIO_2 and positive-pressure ventilation while conserving oxygen supplies. This is a very effective adjunct to total intravenous anesthesia techniques, especially when a muscle relaxant is used.

To understand low-flow anesthesia with oxygen, we must consider the various contributions to the volume of gas in the anesthesia system. The anesthesia system consists of the tubing, reservoir bag, gas in the carbon dioxide absorber, and the patient's functional residual capacity (FRC) (Figure 8-1). For an adult, the volume of gas in this system is approximately 10 L.[4] Several potential positive and negative contributions to this system occur during the anesthetic-delivery period. The patient consumes oxygen from the anesthesia system. Normal adult oxygen consumption (VO_2) is approximately 200 mL/min.[5] Carbon dioxide produced by the patient is removed by the carbon dioxide absorber. During closed-circuit anesthesia, the anesthesia provider closes the relief valve and adjusts the oxygen flow to maintain a *constant volume* in the anesthesia system. Changes in system volume are assessed at end-expiration. When a rising-bellows ventilator is used, system volume is constant when the bellows returns to the same height with each breath. The same principle applies when a reservoir bag is used; however, the extent to which the bag is filled is assessed relative to the anesthesia provider's hand. If the anesthesia system is leak-free, only enough fresh oxygen to replace the patient's consumption is required.

Inward and Outward Leaks

In practice, some leaks usually occur, especially around the face mask or endotracheal tube. Leaks can be either into or out of the circuit (Figure 8-2). A leak into the system can occur when negative pressure develops in the circuit, the most common source being a hanging bellows ventilator. Negative pressure and a potential inward leak can also arise during spontaneous ventilation. An inward leak introduces room air (nitrogen and oxygen) into the circuit. Outward leaks arise when the circuit pressure is positive. During controlled ventilation (ei-
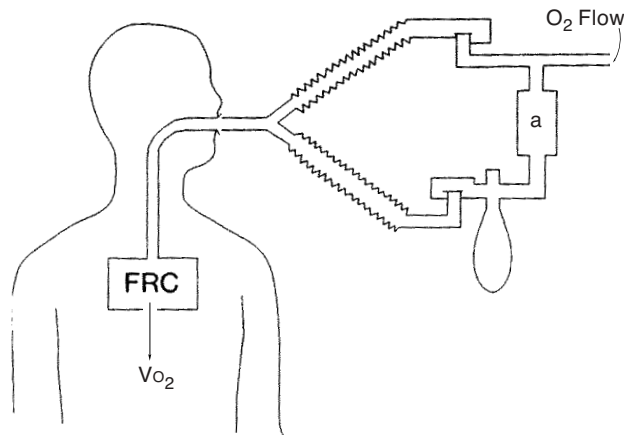

Fig. 8-1. The closed anesthesia system consists of the circuit, reservoir bag, and the patient's functional residual capacity. The total volume of the anesthesia system for an adult is approximately 10 L. If the circuit is free of leaks and the system volume is held constant, oxygen flow will equal oxygen consumption. FRC: functional residual capacity; O_2: oxygen; VO_2: normal adult consumption of oxygen; a: carbon dioxide absorbant.
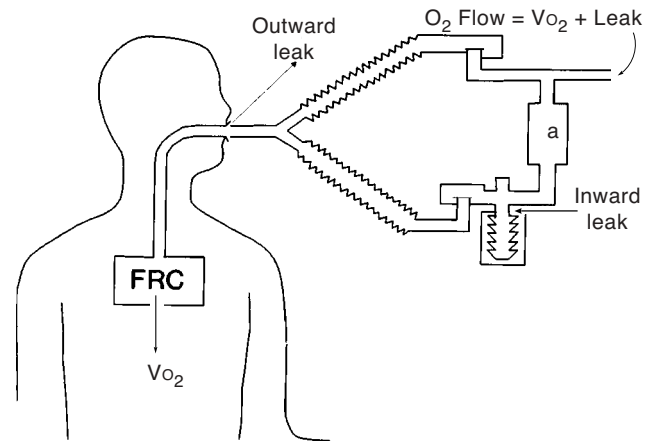

Fig. 8-2. Leaks usually occur in a closed-circuit anesthesia system, including those that incorporate a hanging bellows ventilator. When the system volume is held constant, oxygen flow equals oxygen consumption plus the leak. This is an algebraic sum. An inward leak lowers the oxygen flow required to maintain system volume, while an outward leak increases the required flow. FRC: functional residual capacity; O_2: oxygen; VO_2: normal adult consumption of oxygen; a: carbon dioxide absorbant.

ther manually controlled or using a rising-bellows ventilator), circuit pressure will be positive and any leak will be out of the anesthesia system. A substantial outward leak can also arise when a gas analyzer or mass spectrometer is used (unless the sampled gas is returned to the circuit). In common peacetime practice, gas analysis produces the most substantial leak.

The distinction between inward and outward leaks is important. An inward leak introduces nitrogen into the circuit, which will tend to lower the F_{IO_2} in the system. When the circuit is closed soon after induction, the initial F_{IO_2} is usually 0.5 to 0.6. To understand the effect of an inward leak, consider a patient with a V_{O_2} of 200 mL/min, an initial system F_{IO_2} of 0.5 and an inward leak of 10 mL/min. With an inward leak of 10 mL/min, a fresh-gas oxygen flow of 190 mL/min will maintain the system volume. During each minute, the inward leak introduces 8 mL of nitrogen and 2 mL of oxygen. Each minute, the patient consumes 200 mL of oxygen while 192 mL of oxygen is added to the system. Therefore, the F_{IO_2} will decrease with time. After 1 hour, 480 mL (60 min • 8 mL/min) of nitrogen will be introduced into the system. The circuit initially contained 5,000 mL of nitrogen and 5,000 mL of oxygen, so after an hour it will contain 4,520 mL of oxygen and 5,480 mL nitrogen (F_{IO_2} = 0.452). The F_{IO_2} has decreased by 0.048.

In contrast, outward leaks increase the F_{IO_2} in the system because the leak removes oxygen and nitrogen, which are replaced with oxygen only. Let us again consider a patient whose V_{O_2} is 200 mL/min, and a system with an outward leak of 50 mL/min. To maintain circuit volume, 250 mL of oxygen per minute must be added via the fresh-gas flow. During the first minute, the F_{IO_2} is 0.5; therefore, the leak removes approximately 25 mL of nitrogen, which is replaced with oxygen. After a minute, the circuit will contain 5,025 mL of oxygen and 4,975 mL of nitrogen. The F_{IO_2} will have increased slightly. During the second minute, the leak removes approximately 25 mL [(4,975 ÷ 10,000) • 50 mL = 24.95 mL] of nitrogen. As the system F_{IO_2} increases, less nitrogen is removed in the leak. This change in F_{IO_2} is actually a continuous process that can be summarized by an exponential expression of the form:

$$1 - e^{-t/T_c}$$

where t represents time and T_c represents the time constant, which equals the volume divided by the flow.[6] In this example,

$$T_c = \frac{10,000 \text{ mL}}{50 \text{ mL/min}} = 200 \text{ min}$$

The initial F_{IO_2} was 50% and the F_{IO_2} of the fresh-gas flow entering the circuit is 100%; after one time constant (ie, 200 min), the F_{IO_2} will be 0.835 (ie, 67% of the difference between 50% and 100%); after two time constants (400 min), it will be 0.935 (87% of the difference between 50% and 100%); and after three time constants, it will be 0.975 (95% of the difference between 50% and 100%). Note that with leaks of 50 to 100 mL/min, the F_{IO_2} increase is quite slow. Therefore, when F_{IO_2} is measured during closed-circuit anesthesia, it is quite common to see values of 0.5 to 0.7 despite the fact that the fresh gas is 100% oxygen.

There are two additional sources of nitrogen in the closed anesthesia system. First, nitrogen can enter the closed system from the release of dissolved nitrogen by body tissues. The total nitrogen dissolved in the body is approximately 1 L. Because the volume of the closed system is 10 L, dissolved nitrogen could potentially lower the F_{IO_2} by one tenth (1 L÷10 L). Second, nitrogen remains in the FRC when the circuit is closed. This nitrogen distributes throughout the entire system. As an example, consider an adult patient who is intubated awake with no preoxygenation. The anesthesia circuit contains pure oxygen and the circuit is closed immediately after intubation. The adult patient's FRC is approximately 2 L. Because the patient was breathing room air prior to awake intubation, the F_{IO_2} in the FRC is 21%. Therefore, the FRC contains 1,580 mL of nitrogen (2,000 mL • 0.79). This nitrogen will be distributed throughout the anesthesia system, producing an initial F_{IO_2} of 0.84 [(10,000 – 1580) ÷ 10,000 = 0.84]. In this example, the circuit contained oxygen and the patient's FRC was the source of the nitrogen. If the patient is preoxygenated for several minutes with a tight-fitting face mask, a semiclosed circuit, and high flows of oxygen (4–5 L/min), then the FRC nitrogen can largely be removed, and when the circuit is closed the initial F_{IO_2} will be high (0.7–1.0). If, however, a loose-fitting face mask is utilized, nitrogen will enter around the mask and be distributed throughout the system. The initial F_{IO_2} may then be as low as 0.30 to 0.40.

Conserving Oxygen

With this understanding of the sources and losses of oxygen and nitrogen in the closed circuit, oxygen

can be conserved to a large extent. The following checks are required before using the closed circuit:

1. The circuit should be tested for leaks. The circuit should hold 40 cm H_2O with an inflow of less than 200 mL/min.
2. The carbon dioxide absorbent should be checked. With a double-canister system, the absorbent should not be changed until the indicator has begun to change color in the lower canister. At this point, the bottom canister should be moved to the top and a fresh canister placed in the bottom. Changing canisters when the indicator has changed in only the upper canister will waste substantial amounts of soda lime.[7]
3. The function of the one-way valves should be confirmed since incompetent valves may allow rebreathing of carbon dioxide.
4. The oxygen analyzer, if available, should be calibrated and the low-F_{IO_2} alarm set.

During low-flow anesthesia, we wish to produce a slight outward leak so that the F_{IO_2} will not fall during the case. A hanging bellows ventilator should not be used. If ventilation is controlled, it should be done either manually or with a rising-bellows ventilator. Any leaks will be outward so long as the flows are adjusted to fill the bag or bellows at the end of expiration. Flows of 250 to 350 mL/min should be adequate. If the anesthesia provider finds that larger flows are required to maintain system volume, a search should be made for leaks. Common sources of leaks include around the face mask, around the endotracheal tube, and loose fittings.

Most discussions of closed-circuit anesthesia have emphasized the delivery of nitrous oxide.[8,9] Several of the steps required for the delivery of this relatively impotent anesthetic are no longer required when it is eliminated. Thorough denitrogenation is required if nitrous oxide is used, as any residual nitrogen limits the amount of nitrous oxide that can be given. When only oxygen is being administered, the circuit can be closed after partial denitrogenation (F_{IO_2} of 0.4–0.5). With only outward leaks, the F_{IO_2} will slowly increase during the case. An oxygen analyzer is mandatory when nitrous oxide is a component of the anesthetic. When only oxygen is used, continuous F_{IO_2} monitoring is no longer essential. In the field, oxygen analyzers may not be available or may be in short supply. If available, the analyzers should probably be utilized intermittently to conserve their function. A top priority for their use is confirmation of the contents of newly opened oxygen cylinders. Additionally, they may be helpful to check the initial F_{IO_2} and at intervals during the case to assure that an inward leak has not developed.

POTENT VOLATILE ANESTHETIC AGENTS

Although intravenous agents will probably be the mainstay in field anesthesia, occasions will arise when supplementation with low doses of a potent volatile agent would be desirable. The closed circuit can be used to deliver potent volatile agents while conserving precious oxygen supplies. Closed-circuit administration of potent volatile agents requires a special pharmacokinetic conceptualization.

The intravenous line and the closed anesthetic circuit are both extensions of the patient's vasculature (Figure 8-3). When a drug is injected into the intravenous line, it flows to the vasculature and is distributed to body tissues. For purposes of this chapter, *dosage* is defined as the amount of drug that reaches the vasculature. Because little of the drug is lost in the line, the dose is equivalent to the amount injected. Strictly speaking, dosage should be expressed in moles; however, it is usually expressed as mass (grams, milligrams, or micrograms), which is the amount in moles multiplied by the molecular weight.
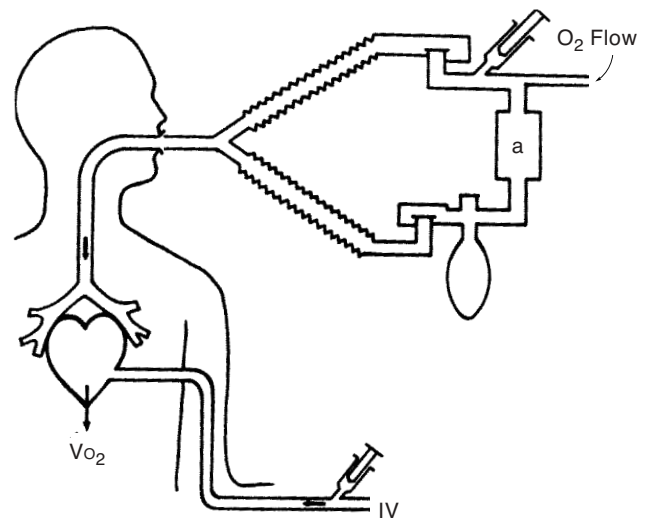

Fig. 8-3. Like the intravenous (IV) line, the closed circuit is an extension of the patient's vasculature. O_2: oxygen; V_{O_2}: normal adult consumption of oxygen; a: carbon dioxide absorbant.

Dosage is defined similarly for volatile anesthetics. Provided that the anesthetic circuit is closed, the fate of volatile agents is straightforward. After it is injected into the circuit, the volatile anesthetic vaporizes, enters the vasculature via the alveolar capillary membrane, and is distributed to body tissues. Except for the amount that primes the circuit, all volatile agent injected into the circuit reaches the patient's vasculature. Therefore, dosage is clearly defined: it is the amount injected into the circuit. Strictly, dosage of a volatile anesthetic should also be expressed in moles; however, because each agent is a pure liquid with a constant molarity, it is more convenient to express dosage as milliliters of liquid, which is equal to the dosage in moles multiplied by the molecular weight and divided by the density. Please note that the various anesthetics vary in potency, molecular weight, and density, so that liquid dosage requirements differ between agents (ie, 1 mL of halothane is not the same as 1 mL of isoflurane, just as 1 mg of fentanyl is not the same as 1 mg of morphine).

If the circuit is not closed, the dosage is still the amount of anesthetic that reaches the patient's vasculature; however, this can no longer be conveniently measured because a large, unpredictable amount escapes via the relief valve. Please note that the concentration of volatile agent in the circuit is *not* the dosage, just as the concentration of an intravenous anesthetic in the intravenous line is not the dosage. In other words, when liquid volatile anesthetics are injected into a closed circuit, the dosage the patient receives is the amount of liquid injected into the closed circuit, just as the dosage of an intravenous agent is the amount injected into the intravenous line.

Pharmacokinetics

With dosage defined, the next question is: How much volatile anesthetic should we give? Inhaled anesthetics display square-root-of-time (SQRT) kinetics.[10,11] When the cumulative dose (in milliliters of liquid) of a potent inhalational anesthetic is plotted against time required to maintain a constant blood concentration, a constant amount of anesthetic (unit dose) is seen to be absorbed in each SQRT interval (0–1 min, 1–4 min, 4–9 min, 9–16 min, etc) (Figure 8-4). These intervals increase in length throughout the case. In the graph, the curve does not pass through the origin because one additional unit dose is required to prime the circuit. When the
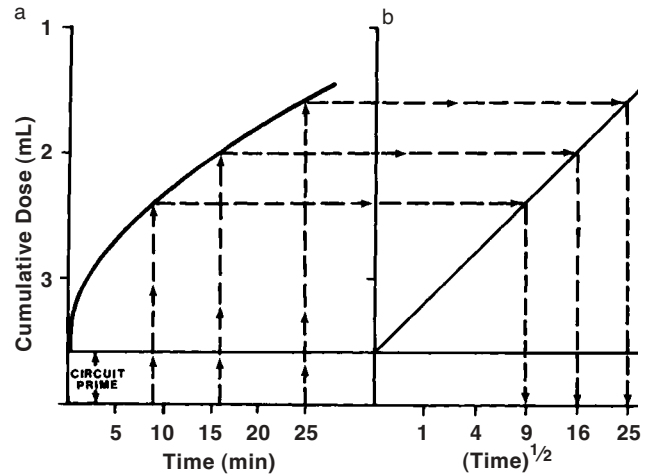

Fig. 8-4. To maintain a constant blood concentration of volatile liquid anesthetic, (**a**) cumulative dose of volatile liquid anesthetic (in milliliters) is plotted against the time required to maintain a constant blood concentration. (**b**) Cumulative dose vs. square root of time (SQRT) yields a straight line.

time axis is transformed to SQRT, the plot becomes linear with a slope equal to the unit dose (UD):

$$(1) \qquad UD = \frac{TD}{1 + \sqrt{t}}$$

where t represents elapsed time in minutes and *TD* represents the cumulative (total) dose in milliliters of liquid. The 1 added in the denominator accounts for the circuit prime.

It is possible to utilize rigid dosage regimens based on the model in which the patient receives a predetermined unit dose at each SQRT interval (0 min, 1 min, 4 min, 9 min, 16 min, etc.). This would be comparable to giving the same predetermined dose of an intravenous agent, such as sodium nitroprusside, fentanyl, or atracurium, to every patient: dosage requirements vary among individual patients; so, while a single infusion regimen treats the average patient, it underdoses some and overdoses others. Dosage requirements for volatile anesthetics also vary among patients. Therefore, except in some experimental situations, it is prudent to adjust administration based on patient response.

SQRT kinetics can be used to assess dosage requirements during anesthesia and to assist the anesthesia provider in adjusting the dose, based on patient response. Figure 8-5 shows the curves obtained when cumulative dosage is plotted against time for two individuals with different dosage re-
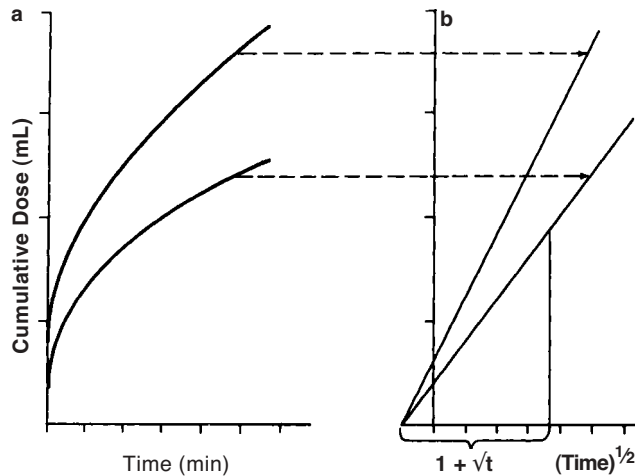
Fig. 8-5. (**a**) Cumulative dose is plotted against time for two individuals with different dosage requirements. (**b**) When cumulative dose is plotted against the square root of time (SQRT), two lines with different slopes are obtained. The slope equals the unit dose.

TABLE 8-1

MULTIPLIERS FOR CALCULATING UD_1

Anesthetic	Multiplier
Halothane	0.029
Isoflurane	0.038
Enflurane	0.062
Diethylether	0.24

quirements; when concentration is plotted against SQRT, lines with different slopes are obtained. The slopes of these lines are the respective unit doses for the two patients.

In many areas of pharmacology, it is customary to index dosage based on patient size. Weight and body surface area (BSA) are two common measures. Although BSA is usually derived from a nomogram or formula involving height and weight, some physiologists believe that the weight expressed in kilograms, raised to the three-fourths power ($kg^{3/4}$), is a more precise parameter.[12] In closed-circuit anesthesia, it has become customary to index dosage based on this physiological BSA–weight relation. The dosage index *f* represents the unit dose from equation 1 indexed for patient size using equations 2 and 3:

$$(2) \qquad f = \frac{UD}{UD_1} = \frac{TD}{UD_1(1 + \sqrt{t})}$$

$$(3) \qquad UD_1 = m \cdot kg^{3/4}$$

The multiplier *m* in equation 3 accounts for differences in density, molecular weight, and potency among the volatile anesthetics and is different for each agent (Table 8-1). In an individual patient, a given dosage index should provide the same depth of anesthesia no matter which inhalational agent is used.

The dosage index *f* can be used to compare dosage requirements between patients. Additionally, since the dosage requirement for an individual patient remains fairly constant, the index guides administration while the patient is receiving the anesthetic. In theory, during a pure inhalational anesthetic procedure, a dosage index of 1 should prevent movement to skin incision in one half of patients, and an index of 1.3 should prevent movement in 95% of patients.[4] In practice, however, various intravenous agents (eg, opioids, benzodiazepines, and muscle relaxants) are utilized, so the required dosage index is much less.

Figure 8-6 shows a frequency distribution of the dosage index *f* during a fentanyl/isoflurane/pancuronium/oxygen anesthetic administered for elective surgery in healthy adults.[13] Note that the mean dosage index was 0.42, with 46 of 52 (88%) patients requiring a dosage index between 0.32 and 0.52. The required dosage index may be lower in patients whose physical status is poor, or when large amounts of intravenous medications are utilized. The dosage requirement is also usually lower during surgical preparation when little stimulus is provided and the effect of induction agents is still present.

Concentration and Dosage

The foregoing discussion of closed-circuit pharmacokinetics was prefaced by a careful definition of dosage. Most anesthesia providers are more accustomed to thinking in terms of *concentration* of volatile anesthetics with semiclosed anesthesia systems. A concentration-response curve (ie, a minimal alveolar concentration [MAC] assay) has become widely used in conceptualizing inhalational anesthetic pharmacology.[14] Because blood concentrations of volatile agents are difficult to measure, the end-tidal concentration is utilized instead.[15] As
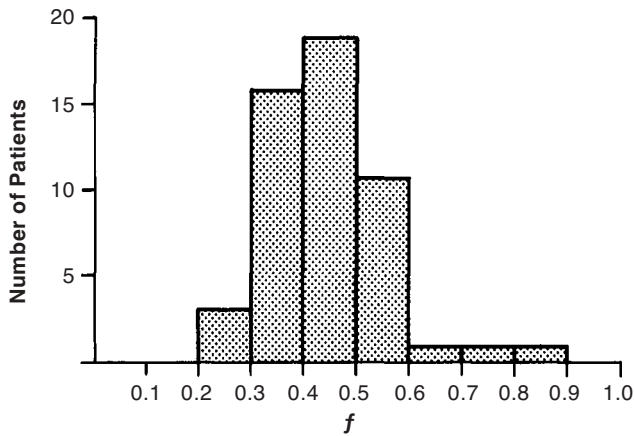
Fig. 8-6. Frequency distribution of dosage index f. Data were extracted retrospectively from 52 anesthesia records in which closed-circuit isoflurane/fentanyl/pancuronium/oxygen technique was utilized. All patients were American Society of Anesthesia categories I and II and were scheduled for elective orthopedic or gynecologic surgery. Anesthesia was induced with thiopental (3–5 mg/kg). Tracheal intubation was facilitated with succinylcholine or pancuronium. Maintenance muscle relaxation was provided with pancuronium. The patients received fentanyl (150–250 μg) during the first hour of anesthesia. After intubation, the circuit was closed and isoflurane was administered by liquid injection, guided by clinical signs of anesthesia. The dosage index was recorded every 10 to 15 minutes on the anesthesia records. The mean dosage index during the first hour of surgical stimulation was extracted from each record; these values were used to construct the frequency distribution. Reprinted with permission from Baumgarten RK, Elms MK. Dosage requirements for closed circuit anesthesia. In: Bergmann H, Kramar H, *Beiträge zur Anaesthesiologie und Intensivmedizin*. Vol 7. In: *European Congress of Anaesthesiology*. Vienna, Austria: Verlag Wilhelm Maudrich; 1986: 55. Abstract 107.

would be expected, the dose-response curve (Figure 8-7) for volatile anesthetics is very similar to the MAC assay.

The Pharmacological Uncertainty Principle

With the proliferation of mass spectrometers now being used in clinical anesthesia, many anesthesia providers are now accustomed to adjusting the end-tidal concentration to achieve the desired depth of anesthesia. It might be attractive to measure both dosage and end-tidal concentration during closed-circuit anesthesia; however, this is very difficult
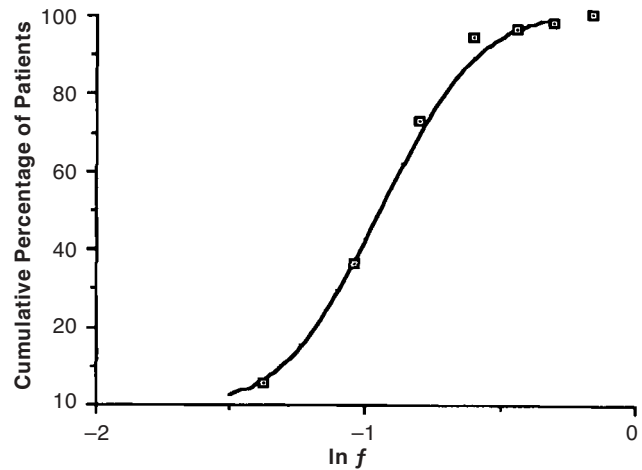

Fig. 8-7. The data from Fig. 8-6 were used to construct this dose-response curve for isoflurane. The frequency histogram is reexpressed as cumulative percentage versus the natural logarithm of f (ln f).

with current equipment. Because one of the largest leaks in anesthesia equipment is the gas removed by a mass spectrometer, it is no longer possible to assess dosage accurately. Therefore, we can either know the dosage or the concentration but not both. This is analogous to Heisenberg's principle: one can precisely measure the position or the momentum of a subatomic particle, but not both. The advent of stand-alone monitors that can return sampled gas to the circuit should make it possible to measure concentration and dosage simultaneously. This may be very useful for teaching closed-circuit anesthesia.

With adult patients, leaks of 50 to 100 mL/min are tolerable because the amount of agent lost in the leak is small relative to the amount absorbed by the patient. This is important, as small leaks are useful to assure that any leak is outward. (With pediatric patients, leaks are more serious because the amount lost in even a small leak is significant compared with the patient's smaller dosage requirement. When closed-circuit anesthesia is used with small children, a tight-fitting face mask is necessary to prevent leaks, and a tuberculin syringe is used to deliver small, incremental doses of anesthetic agent to the circuit.[16]

Equipment for Administering Volatile Agents

We have emphasized the importance of knowing

the dosage of volatile agent administered to the patient. Although vaporizers can be used for closed-circuit anesthesia, they can also introduce some complexity. When a vaporizer is used, molar dosage rate will depend on the vaporizer setting. To obtain the cumulative dose, the anesthesia provider must add all the various settings that have been used and multiply by the time that each was used—a cumbersome task. Liquid injection eliminates these difficulties.[11] The cumulative dose is readily apparent by subtracting from the amount remaining in the syringe. Additionally, the molar dose is the same at any ambient temperature and pressure, as this only depends on the molecular weight and the density of the liquid, which are constant. Molar dosage does not depend on vapor pressure. This is important because vapor pressure varies dramatically over the range of ambient pressures and temperatures in which field anesthesia may be practiced. The molar output of many vaporizers, especially the copper kettle, increases substantially with increasing temperature.[17]

In the case of in-circuit vaporizers, dosage rate will also depend on the oxygen flow rate (see Figure 8-3). It may be difficult to assure the accuracy of flowmeters in field medical treatment facilities. With liquid injection, the dose does not depend on the oxygen flow rate, just as the dose of an intravenous agent will not depend on the intravenous flow rate.

It is vitally important to prevent accidental intravenous injection of liquid volatile anesthetic agents. Prominent labeling is crucial. At one time, injection ports were commercially available and the syringe could be left in the port throughout the case[18]; however, the port was interchangeable with intravenous fitting so the potential for intravenous injection still existed. An injection port can also be fabricated from a metal T-piece.[9] An expedient injector is pictured in Figure 8-8. A disposable syringe is used with a long needle, either an 18-gauge spinal needle or the introducer from a 16-gauge intravenous cannula. The long needle facilitates drawing up the liquid anesthetic from the bottle. The injector is inserted into the tubing, in either the inspiratory or the expiratory limb, and left in place. Therefore, it is very unlikely that it will be interchanged with other syringes. The needle never leaves the syringe and its length draws attention—the contents of this syringe are unusual and not for intravenous injection. With disposable syringes, the plunger swells slightly on contact with volatile agent so that it will not release agent into

Fig. 8-8. Note the prominent label on this expedient liquid injector. The large needle facilitates filling the syringe and advertises that this is not a syringe intended for intravenous injection. The syringe remains in the circuit and is not placed with other syringes. If the syringe requires refilling, a new location in the tubing can be used for reinsertion.

the circuit without the plunger's being purposefully pushed.

Square-Root-of-Time Kinetics for Intravenous Agents

Because the dosage concept (see Figure 8-3) applies to both closed-circuit and intravenous administration, it is quite possible that the pharmacokinetics of volatile and intravenous anesthetics are quite similar. Intravenous agents are usually described with linear multicompartmental models; infusion schemes that produce constant blood levels in these models have been described.[19,20] These schemes consist of an initial bolus followed by an exponentially decreasing infusion. Using these equations, the cumulative dose was plotted against time for two typical intravenous agents, lidocaine[21] and fentanyl[22,23] (Figures 8-9 and 8-10). When these curves are transformed to SQRT, an excellent
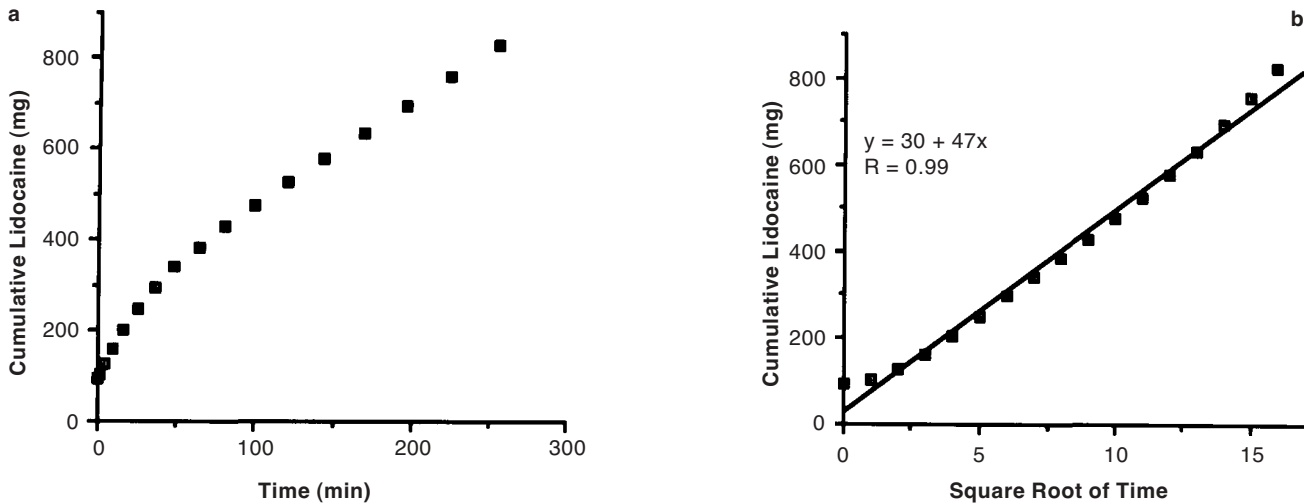
Fig. 8-9. (**a**) Cumulative dose of lidocaine is plotted against time, from a pharmacokinetic simulation with a target concentration of 3 µg/mL. A two-compartment open model was used with an initial bolus followed by an exponentially decreasing infusion. (**b**) Cumulative dose of lidocaine plotted against the square root of time (SQRT). Note that the slope of the line (ie, the unit dose) is 46 mg. Data source: Riddel JG, McCallister GB, Wilkinson GR. A new method for constant plasma drug concentrations: Application to lidocaine. *Ann Int Med*. 1984;100:25–28.

linear fit is achieved over the first 3 to 4 hours of administration. Thus, the SQRT model may also apply to intravenous agents. As anesthesia providers become more comfortable with intravenous anesthesia based on adjusting dosage to patient response, the generalization to dosage-based administration of volatile anesthetics may become easier.
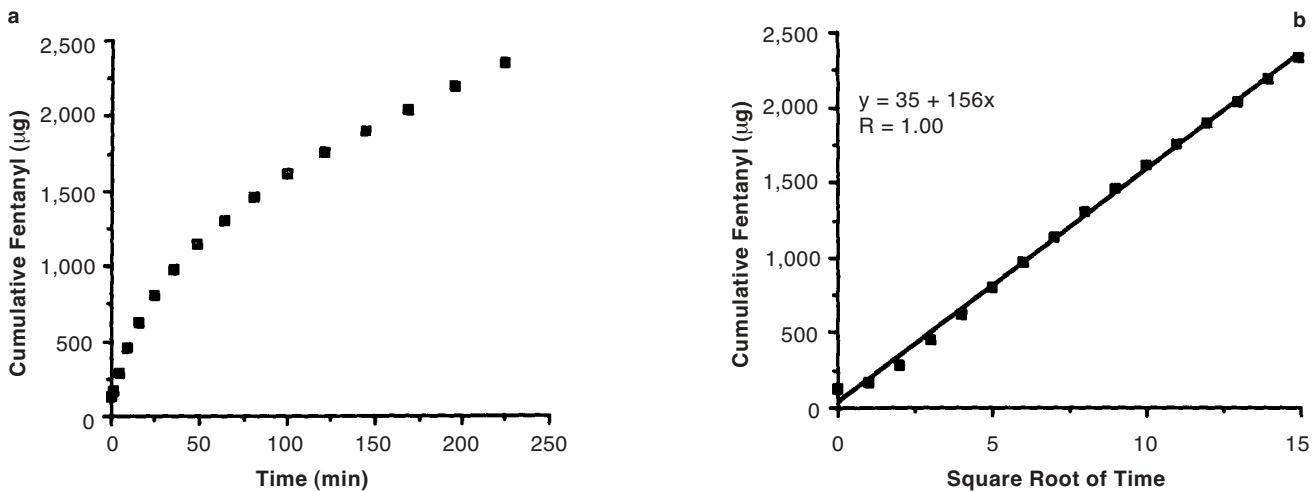

Fig. 8-10. (**a**) Cumulative dose of fentanyl plotted against time, from a pharmacokinetic simulation for a 70-kg subject with a target concentration of 5 ng/mL. A three-compartment open model was used. (**b**) Cumulative dose of fentanyl plotted against the square root of time (SQRT). The unit dose equals 156 µg. Data sources: (1) Alvis JM, Reves JG, Govier AV. Computer assisted continuous infusions of fentanyl during cardiac anesthesia: comparison with a manual method. *Anesthesiology*. 1985;63:41. (2) McClain DA, Hug CC. Intravenous fentanyl kinetics. *Clin Pharmacol Ther*. 1980;28:106–114.

SUMMARY

Compressed oxygen will probably be in short supply in many deployment situations. Nitrous oxide will not be available at all. Simplicity and ease of use are also important in difficult settings. Therefore, the use of the closed circuit to provide a high FIO$_2$ during anesthesia is a valid and practical approach to the management of casualties in field medical treatment facilities. Closed-circuit delivery of anesthetic agents can be used as an adjunct to intravenous techniques with which the anesthesia provider is already familiar. This approach can conserve limited supplies of compressed gas. Additionally, the pharmacokinetic analogy between intravenous and potent volatile anesthetics may be used to balance intravenous techniques with moderate doses of inhalational anesthetics.

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