A Simple Apparatus for Accelerating Recovery from Inhaled Volatile Anesthetics

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Hyperpnea increases anesthetic elimination but is difficult to implement with current anesthetic circuits without decreasing arterial P_{CO_2}. To circumvent this, we modified a standard resuscitation bag to maintain isocapnia during hyperpnea without rebreathing by passively matching inspired P_{CO_2} to minute ventilation. We evaluated the feasibility of using this apparatus to accelerate recovery from anesthesia in a pilot study in four isoflurane-anesthetized dogs. The apparatus was easy to use, and all dogs tolerated being ventilated with it. Under our experimental conditions, isocapnic hyperpnea reduced the time to extubation by 62%, from an average of 17.5 to 6.6 min ($P = 0.012$), but not time from extubation to standing unaided. This apparatus may provide a practical means of applying isocapnic hyperpnea to shorten recovery time from volatile anesthetics.

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Hyperventilation increases the rate of elimination of volatile anesthetics (1–3), but it also decreases arterial P_{CO_2}, which, in addition to causing post-hyperventilation apnea, decreases cerebral blood flow (4), prolonging washout of anesthetic from the brain. Hyperpnea could be clinically useful for facilitating recovery from volatile anesthetics if the disadvantages of hypocapnia could be prevented. Maintaining isocapnia during hyperpnea (without rebreathing) cannot readily be accomplished with any known anesthetic circuit. Simply adding CO_2 to a circle anesthetic circuit is impractical because, unless the flow of CO_2 is precisely regulated to match the minute ventilation ($\dot{V}_E$) to maintain isocapnia, hypercapnia may occur (5).

In 1998, our group described a simple circuit that clamps P_{ETCO_2} of a spontaneously breathing subject despite increases in $\dot{V}_E$ (isocapnic hyperpnea; IH) by passively increasing inspired P_{CO_2} in proportion to $\dot{V}_E$ (6). Using the same underlying principle (see below), we made a simple modification to a standard resuscitation bag and then performed a pilot study in isoflurane-anesthetized dogs to assess the feasibility of using IH to accelerate recovery from anesthesia.

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Methods

A standard resuscitation bag (Laerdal, Stavanger, Norway) was modified by providing a source of 6% CO_2 and 94% oxygen (reserve gas) to its low-pressure relief valve via a demand regulator (SCUBAPRO 350; Scubapro, El Cajon, CA) (isocapnia attachment; Fig. 1).

Gas is provided to the resuscitation bag from two sources—fresh gas (100% oxygen) supplied at a set flow (fresh gas flow, FGF) and reserve gas supplied on demand. At $\dot{V}_E$ equal to or less than the FGF, the apparatus functions as an unmodified resuscitation bag, providing 100% oxygen. However, when $\dot{V}_E$ increases above FGF, whether spontaneously or as a result of manually assisted ventilation, the balance of the inspirate consists of reserve gas drawn through the low-pressure relief valve. The concentration of CO_2 in the reserve gas provides a minimal gradient for CO_2 elimination. Because of the concentration of CO_2 in the reserve gas, the gradient for CO_2 elimination is minimized, thereby maintaining isocapnia. Therefore, alveolar ventilation ($\dot{V}_A$) and, hence, CO_2 elimination, will depend primarily on FGF and be relatively independent of the volume of reserve gas breathed. Because neither the FGF nor the reserve gas contains any anesthetic, they both contribute to the washout of anesthetic gas from the lung.

After institutional ethics board approval, we studied four mongrel dogs (25–38 kg) of either sex by using a cross-over protocol, with each dog serving as

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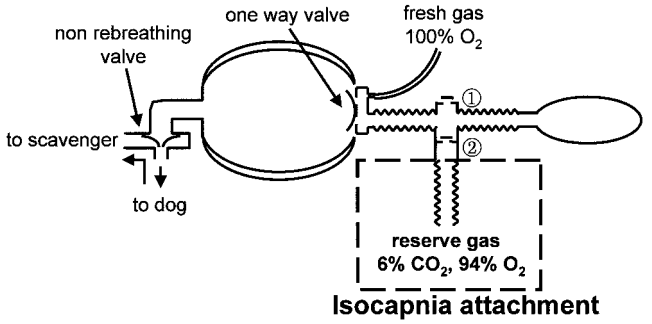

Figure 1. Isocapnic hyperpnea apparatus composed of a standard resuscitation bag which includes a high- (1) and a low- (2) pressure relief valve with an isocapnia attachment.

its own control. Experiments were performed in an animal surgical suite with facilities similar to those in operating rooms in our institution. Anesthesia was induced with methohexital 5 mg/kg IV. The trachea was then intubated and the dogs ventilated for 90 min via a circle anesthetic circuit with oxygen flow set at 4 L/min. Anesthesia was maintained with isoflurane in oxygen. The output of the isoflurane vaporizer was adjusted to give an end-tidal concentration of 2.5% (corresponding to 1.7 minimum alveolar anesthetic concentration [MAC]) (3), and the ventilation was adjusted to maintain P_{ETCO_2} at 40 mm Hg. Each dog was anesthetized on two separate occasions separated by at least 2 days. The following variables were monitored: arterial blood pressure (maintained >100 mm Hg when necessary with ephedrine), ventilatory flow, airway CO_2 and isoflurane concentrations (Capnomac Ultima; Datex Engstrom, Helsinki, Finland), oxygen saturation, and rectal temperature. We maintained oxygen saturation >98% and temperature within 1°C of the initial value. Airway P_{CO_2}, isoflurane concentration, and flow were digitized and recorded.

After 90 min of anesthesia, the animal was disconnected from the anesthetic circuit and recovered with either of two methods, randomized as to order. For the first (control recovery), we used intermittent manual ventilation with a standard resuscitation bag supplied with 100% oxygen (1–4 L/min as necessary to keep P_{ETCO_2} <50 mm Hg) until spontaneous ventilation returned. Thereafter, the dog was allowed to breathe spontaneously through the resuscitation bag until it no longer tolerated the endotracheal tube. The P_{ETCO_2} was allowed to increase to a maximum of 50 mm Hg, simulating clinical practice. For the second (IH recovery), we applied IH with the apparatus at approximately three times the dog's $\dot{V}_E$ under anesthesia. FGF was set to approximately half the dog's $\dot{V}_E$ while ventilated under anesthesia to allow P_{ETCO_2} to increase to a level similar to that during control recovery. If spontaneous ventilatory efforts returned, assisted breaths were synchronized with the dog's efforts until it would no longer tolerate the endotracheal tube. Expired gas was directed to the scavenger.

Recovery from anesthesia was assessed each minute by sweeping the cornea with gauze and pinching the tail with a spring clamp. The dog was tracheally extubated when it roused and would no longer tolerate the endotracheal tube, as indicated by violent coughing and shaking of its head. As recovery progressed, the dog was continuously encouraged to stand. The times to both extubation and the ability to stand unaided were noted. All times were determined by reviewing a videotape of the emergence from anesthesia.

A paired Student's *t*-test was used to compare the times to extubation and times to stand unaided during the two recovery protocols.

Results

The apparatus was as easy to use as a resuscitation bag alone. The dogs tolerated manual ventilation at hyperpneic levels with the apparatus. P_{ETCO_2} values during control recovery and during IH recovery did not differ (45.1 ± 0.8 mm Hg and 45.1 ± 1.5 mm Hg, mean ± SE, respectively).

The end-tidal isoflurane concentration decreased more rapidly during IH recovery as compared with control recovery (Fig. 2). The mean time to extubation decreased by 62%, from an average of 17.5 to 6.6 min ($P = 0.012$) (Fig. 3). The mean time from the end of anesthetic administration to standing unaided was reduced 40%, from 31.0 to 18.5 min ($P = 0.018$); this was caused mainly by the decrease in time to tracheal extubation, because there was no difference in the time from extubation to standing between control and IH recoveries. There were no differences between groups in total ephedrine dose or body temperature at time of arousal. After IH, there was no posthyperventilation apnea.

Discussion

Our apparatus was straightforward to use in an operating room setting, and IH was well tolerated by the dogs. Our study also confirms long-standing predictions that IH accelerates recovery from isoflurane anesthesia.

Although the effect of IH on the actual times of clinical recovery would have varied from those in our model had we changed such factors as the anesthetic vapor used, inspired concentration, duration of anesthesia, and the use of adjuvant anesthetics (e.g., benzodiazepines, narcotics, or N_2O), the ease of application of the apparatus at the end of anesthesia would have been little affected. This apparatus may therefore be a useful adjuvant during the recovery phase from anesthesia with different volatile anesthetics.

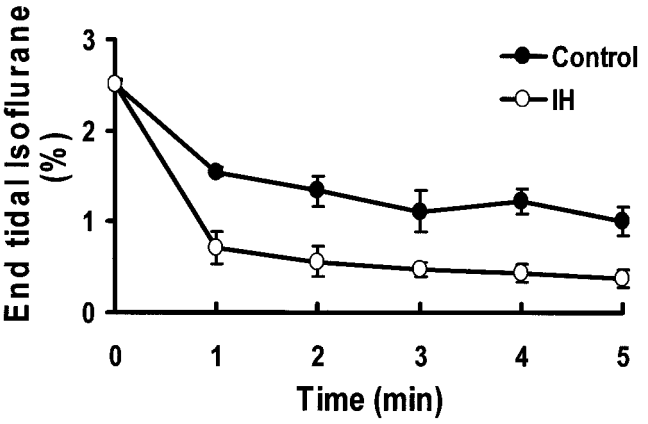

Figure 2. End-tidal isoflurane concentration (mean ± SD) versus time for the first 5 min of control and isocapnic hyperpnea (IH) recovery for all dogs.

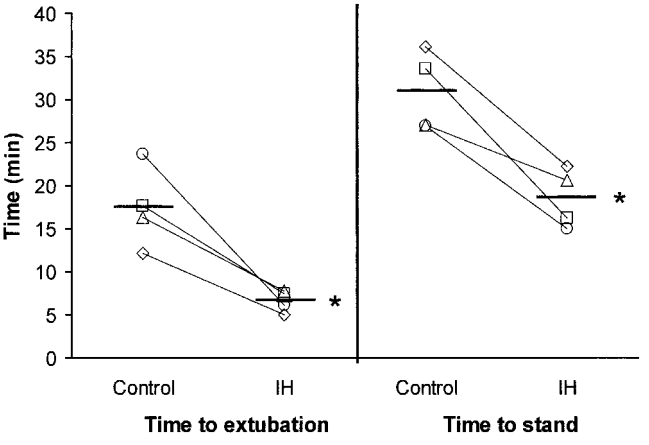

Figure 3. Times to extubation and unaided standing in dogs during control and isocapnic hyperpnea (IH) recovery. Each symbol represents a single dog; lines indicate mean values. *$P < 0.02$.

In this pilot study, we used our apparatus to decrease the alveolar concentration of anesthetic without decreasing the P_{CO_2} and observed the dogs' recoveries. Hyperventilation with currently available anesthetic circuits can result in either maintenance of isocapnia (Mapleson "D") or hypocapnia (circle circuit), but in either case, limitation of FGF results in rebreathing of anesthetic and thus failure to increase anesthetic elimination. The effects of hypocapnia on the time required for recovery from anesthesia may offset those of decreased alveolar anesthetic concentration for two main reasons. First, hypocapnia decreases cerebral blood flow (4), which would decrease the rate of vapor anesthetic washout for a given brain-blood partial pressure gradient. Second, hypocapnia can result in posthyperventilation apnea, during which anesthetic mobilized from tissues is not eliminated via the lungs. Although Stoelting and Eger (2) demonstrated that hyperventilation decreases the alveolar concentration of various vapor anesthetics in dogs, they did not control

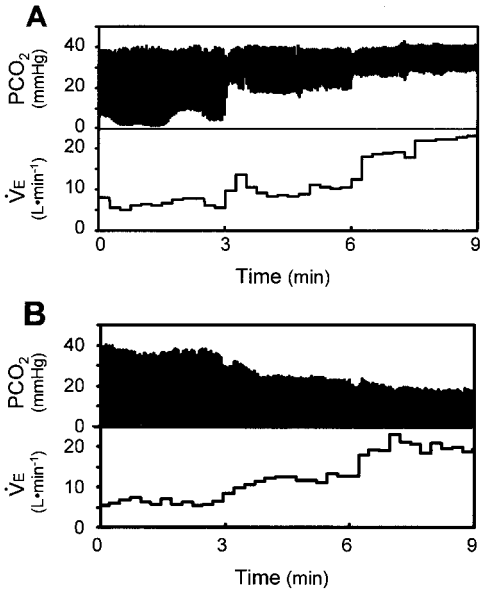

Figure 4. Effects of progressively increased ventilations ($\dot{V}_E$) on airway P_{CO_2} in a volunteer breathing through our apparatus (A) and a standard resuscitation bag (B). Fresh gas flow was set equal to the subject's resting $\dot{V}_E$. With our apparatus, inspired P_{CO_2} increased in proportion to the increase in $\dot{V}_E$, and P_{ETCO_2} remained constant. With the standard resuscitation bag, P_{ETCO_2} decreased as $\dot{V}_E$ increased. Traces: top = airway P_{CO_2}; bottom = $\dot{V}_E$ (calculated every 15 s from expiratory flow).

the dogs' P_{CO_2} during hyperventilation and did not observe their dogs' clinical recovery from anesthesia.

The efficacy of this circuit is depicted in Figure 4, in which we compare, in a human, the effect on airway P_{CO_2} at progressively greater $\dot{V}_E$ with (Fig. 4A) and without (Fig. 4B) the isocapnia attachment. With the attachment, P_{CO_2} did not increase despite the increasing contribution of the reserve gas (containing CO_2) to the subject's $\dot{V}_E$ because the addition of CO_2 is proportional to the increase in $\dot{V}_E$. Similarly, if the subject then decreased his ventilation back toward resting, his P_{CO_2} would not increase because the proportion of $\dot{V}_E$ made up of reserve gas would also decrease proportionally. This approach to maintaining isocapnia represents a marked departure from previous attempts, in which CO_2 was added to all the inhaled gas independent of $\dot{V}_E$. The advantages of IH cannot be duplicated by ventilation with carbogen (or reserve gas) alone because alveolar ventilation (and hence P_{ETCO_2}) would remain a function of $\dot{V}_E$.

This method has the potential to expand the range of techniques available to the clinician even in the era of new low-solubility anesthetic vapors. The per milliliter cost of isoflurane is still, at most, one-fifth that of the new low-solubility anesthetic vapors and is even less expensive when considered on the basis of number of milliliters per minute required to maintain MAC for a given FGF. It may make pharmacoeconomic sense to maintain anesthesia in long surgical cases with isoflurane instead

of desflurane or sevoflurane, particularly when the only advantage of the latter over isoflurane is the shortened recovery. In addition, our method may be effective when applied to sevoflurane to further shorten its recovery profile. Outside the operating room, IH can be used to increase the rate of elimination of CO (7) and ingested volatile hydrocarbons (8).

In summary, we modified a standard resuscitation bag to maintain isocapnia by supplying a gas containing a mixture of oxygen and CO_2 to its inspiratory relief valve. This apparatus was successfully used to accelerate recovery from isoflurane anesthesia in dogs. Our experience indicates that this apparatus should be easy to use in the operating room and that a trial of IH in the clinical setting is warranted.

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