CARDIOPULMONARY EFFECTS OF REBREATHING AND NONREBREATHING ANESTHETIC SYSTEMS DURING HALOTHANE ANESTHESIA IN THE CAT

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ABSTRACT

CARDIOPULMONARY EFFECTS OF REBREATHING AND NONREBREATHING ANESTHETIC SYSTEMS DURING HALOTHANE ANESTHESIA IN THE CAT

By

Sandee M. Hartsfield

Cardiopulmonary variables were measured and differences were evaluated for three groups of six cats anesthetized with halothane in oxygen. The groups varied only in the system used for maintenance of anesthesia and in the total oxygen flow to the systems. Group I was maintained on a pediatric circle CO_2 absorption system with an O_2 flow of 0.5 l/min, Group II was maintained on an Ayre's T-piece system with an O_2 flow of 3 l/min and Group III was maintained on an adult circle CO_2 absorption system with an O_2 flow of 0.5 l/min. Cardiac output, cardiac index, stroke volume, heart rate, peripheral vascular resistance, arterial pressure and venous pressure were the cardiovascular variables measured. Respiratory measurements included end-expired halothane, respiratory rate, end-expired CO_2, arterial PCO_2, arterial PO_2, arterial pH, oxygen saturation and base deficit. Inspired halothane concentration and temperature of arterial blood were also monitored. Each animal was chronically implanted with femoral artery and jugular vein catheters and with an aortic thermistor probe implanted via a carotid artery for thermal dilution cardiac output determinations. Anesthesia was induced with halothane and O_2 by mask, animals were intubated with endotracheal catheters and end-expired halothane concentration was

maintained at 1.4%. Control measurements were recorded immediately prior to anesthesia induction and measurements were recorded every 30 minutes over a 135 minute period.

Control measurements were similar for all variables for the three groups. Cardiovascular and respiratory variables were not statistically or clinically different for the three groups during anesthesia. Changes from control in each group were related to halothane anesthesia. The conclusion of this study was that the three systems tested were not significantly different based on the variables measured during halothane-O_2 anesthesia in healthy cats.

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Sandee M. Hartsfield

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INTRODUCTION

Both rebreathing and nonrebreathing anesthetic apparatus have been widely used in veterinary and human anesthesiology. Although general anesthetics have been shown to depress cardiovascular and respiratory functions,[14] the effects of anesthetic systems on cardiovascular and respiratory functions of anesthetized patients have not been fully elucidated.

Resistance to air flow, dead space and gas flow rates of anesthetic systems have been incriminated as influences on cardiopulmonary responses of anesthetized patients.[3,63,65] The importance of these factors has been related to patient size, tidal volume and respiratory minute volume.[66] Also, the preanesthetic condition of a patient has been incriminated to influence responses with any anesthetic system.[62] Past investigations concerning anesthetic systems have failed to provide all of the needed information for several reasons. First, control data in these studies have been almost entirely lacking. Second, blood gas measurements have not been made simultaneously with pulmonary gas measurements. Third, many studies have utilized only mechanical or mathematical models. Finally, studies using actual patients have not limited induction and maintenance of anesthesia to a single agent nor have they monitored alveolar anesthetic concentrations to allow estimation of blood and brain concentrations.[22] Therefore, there has been little information about changes during anesthesia related solely to systems.

There has been clinical conflict in both human and veterinary medicine concerning the type of system best suited for small patients[27,34,65,66] because of this lack of data. Human anesthesiologists have questioned the use of adult circle systems for premature infants and other children. Therefore, nonrebreathing systems and specially designed pediatric circle systems have been developed for pediatric use. The use of nonrebreathing systems for these patients has been strongly advocated.[3,65,66] Several models of nonrebreathing systems have become available, such as the Stephens-Slater unit,[a] the Magill unit,[b,13] the Ayre's T-piece[c] and the Norman Mask Elbow.[d] Anesthetic apparatus of various designs have been used for administration of inhalation anesthetics in veterinary medicine because of body weight and surface area variations encountered within and between species. Rebreathing systems have been adapted for use in dogs and horses.[14] Nonrebreathing systems, including those listed above, have been advocated for cats and small dogs.[14,62] However, the weight range for use of these systems has been a matter of opinion and conjecture. Some anesthesiologists have suggested use of nonrebreathing systems in animals weighing less than 12-15 lbs.[56,62] However, many veterinarians have continued to use adult circle systems for anesthesia in small patients. The Ayre's T-piece has been advocated to be the most satisfactory system for inhalation anesthesia in cats.[63] The Norman Elbow

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[a]Stephens-Slater Valve, Foregger Company, Smithtown, New York.

[b]Magill System, Med-Flo, Incorporated, Danbury, Connecticut.

[c]Bissonnette Ayre's T, Fraser Sweatman, Lancaster, New York.

[d]Norman Mask Elbow, Dupaco, Incorporated, San Marcos, California.

has been designed to contain less dead space than the Ayre's T-piece and to be desirable for very small animals. Finally, pediatric circle systems have been advocated for veterinary anesthesiology.[34]

Because of the lack of cardiopulmonary data related specifically to anesthetic systems, this study was instituted. The cat was selected as the animal model because of its size, availability and common use as a laboratory animal. Three systems including an adult circle CO_2 absorption system, a pediatric circle CO_2 absorption system and an Ayre's T-piece nonrebreathing system were chosen for study to provide information for both human and veterinary anesthesiologists. The adult and pediatric circle systems were chosen to compare two types of rebreathing systems. The Ayre's T-piece was included to compare rebreathing and nonrebreathing systems.

A rebreathing system has been defined as one in which all or part of the exhaled anesthetic gases pass back into the system[62] to be reused by the anesthetized animal, and circle systems have been defined as rebreathing systems. Circle systems have consistently incorporated a rebreathing bag, a canister for carbon dioxide absorption, two unidirectional valves, two breathing hoses, a "pop-off" or overflow valve and a fresh gas inlet on the inspiratory side of the system. The circle systems, like nonrebreathing systems, have been provided with a fresh gas source, vaporizer, pressure reducing valve and flow meters.[56] By Moyer's classification,[42] circle systems have been grouped as either closed or semiclosed systems since rebreathing may be either complete or partial depending on the rate of fresh gas flow. A closed circle has been defined as one allowing total rebreathing with no leaks in the system.[16] In such a system, the metabolic demands of the animal have determined the oxygen flow, and gases in the reservoir bag must be adequate to supply the tidal volume of the animal. The definition of a semiclosed circle has provided for partial escape of expired gases through the "pop-off" valve. This system has been considered less economical but safer since the inspired concentration of anesthetic has been shown to increase at any vaporizer setting in a closed system.[62] When very high flow rates have been used (5-10 l/min), a nonrebreathing system has been approached due to escape of gases through the "pop-off" valve. With a circle system, the vaporizer placement has varied being either out-of-the-circle or in-the-circle. The out-of-the-circle vaporizer has been commonly used allowing the vaporizer output to be determined solely by the anesthetist. The vaporizer in this position was used in this study, and vaporizer output was not affected by changes in ventilation, allowing the use of low gas flows without increased inspired concentration of anesthetic.[63]

With a nonrebreathing system such as the Ayre's T-piece, elimination of used gases has been by exhalation into room atmosphere. By Moyer's classification,[42] this system using a reservoir bag has been classified as semiopen. Hamilton's method of classification,[29] naming the system and the total flow, has been more applicable in describing such systems. Ayre'sT-piece was developed for use in plastic surgery involving human infants.[3] Various modifications have been made since the original T-piece was used. In babies, Ayre[3] observed that use of this system decreased respiratory rate, improved membrane color, and decreased signs of shock during recovery more than in those babies maintained on "closed oxygen-nitrous-oxide-ether" units. The Ayre's T-piece has consisted of one arm to receive a unidirectional flow of oxygen and anesthetic agent, a second arm to join the endotracheal tube and a third arm to serve as a portal for expiration and to allow connection of an open end reservoir tube. Depending on the anesthetic agent employed, various types of vaporizers have been utilized with the T-piece, and the system has been easily adapted for the initiation of positive pressure ventilation[30] by closing and compressing a vented reservoir bag.

In evaluation of either rebreathing or nonrebreathing anesthetic systems for use in small animals such as cats, several factors related to patient size have been considered. First, the tidal volume has been reported to range from 12-15 ml in 4-7 lb cats.[14] Inspiratory minute volumes ranged from 187-675 ml/min.[6] Because of these low volumes, dead space and resistance in anesthetic systems have been considered important. Flow rate, weight of valves, function of valves, total volume of the system, CO_2 absorbers and function of the "pop-off" valve have been included as factors which would increase the resistance in an anesthetic system.[35] Finally it has been recognized that all anesthetics used in these systems cause respiratory depression[14] inhibiting the quality of alveolar ventilation which may be especially important in small patients.

In considering their use in small patients, the Ayre's T-piece and the circle systems have been compared mechanically and functionally. One advantage of the circle system, adult or pediatric, has been related to low gas flows and lower volume of anesthetic used. Therefore, economics have favored the use of this type of system. Both the circle and the Ayre's T-piece have been designed to provide for elimination of carbon dioxide, monitoring of respiration and positive pressure ventilation. In comparison to circle units, the T-piece has been made relatively simple and obviously less likely to malfunction.

Because of this simplicity, the initial cost of a T-piece has been much less than that of a circle system. The bulk or physical size of the T-piece, as compared to a circle, has made it convenient to use for small patients. A disadvantage of the T-piece has been the loss of heat and water vapor to room atmosphere which has been less of a problem with circle systems. However, the T-piece has not allowed accumulation of water vapor to affect the system's function. Pediatric and adult circle systems have been compared, and the pediatric unit has been favored because of decreased dead space, resistance and valve weight.[1,66] Also, the pediatric circle has provided more visible monitoring of small patients. However, no physiological comparison of patients maintained on the three systems has been made.

The purpose of this study was to compare the effects of the pediatric circle, the adult circle and the Ayre's T-piece systems on cardiopulmonary variables of anesthetized cats. Each animal served as its own control and received only halothane anesthesia. The study was designed to provide new and more meaningful data concerning the inherent effects of anesthetic systems to provide physiological guidelines for choosing anesthetic systems for small patients.

REVIEW OF LITERATURE

The Ayre's T-piece System

Ayre[3] first described the use of a T-piece for administering "open anesthesia" to babies undergoing harelip and cleft palate operations. He described the apparatus involved as a metal T-piece connected by about 1 in of rubber tubing and a metal angle-piece to a Magill endotracheal tube. The inlet portion of the T-piece connected to an apparatus delivering continuous oxygen flow with ether vapor. The remaining opening formed an outlet through which to-and-fro respiration could take place. About 10 in of rubber tubing was attached to this expiratory limb for monitoring the patient's respiration. The metal angle-piece previously mentioned prevented kinking of the rubber tubing due to surgical manipulations. The oxygen flow used was 1.5 to 2 l/min. Four advantages of this system were listed as follows: 1) There was no obstruction to free respiration by valves; 2) Only air, oxygen and a small amount of ether was delivered preventing anoxemia related to nitrous oxide; 3) The amount of rebreathing was adjusted by altering the length of the rubber tubing attached to the outlet of the T-piece; and 4) Vascular congestion and hemorrhage at the surgical site were reduced decreasing chances of postoperative shock. Also, clinical observations were reported comparing the use of the T-piece and "closed circuit" systems. With "closed nitrous oxide-oxygen-ether anesthesia," some babies did well, but others showed rapid respiration, pallor, sweating, dark congested oozing at the operative site and postsurgical shock. However, the T-piece improved the respiratory rate to near 40/min instead of 80/min, improved mucous membrane color, decreased vascular congestion, and yielded fewer postoperative complications. Ayre believed that breathing against expiratory valves and a rebreathing bag would exhaust a weak infant especially during anesthesia greater than one hour. He stated that excess accumulation of respired products hampered pulmonary ventilation leading to more rapid deterioration of the patient especially in babies who normally had increased basal metabolism and decreased percentages of hemoglobin.

Kelsall[38] reported on a modification of the T-piece which eliminated angled connectors and excessive rubber tubing and further decreased resistance to respiration imposed by the system. The apparatus, initially developed for neurosurgical procedures, consisted of a metal tube 1.25 in long and 1 in external diameter. One end of the tube was tapered to fit an endotracheal catheter. The other end was tapered on the outside to take a standard expiratory valve mount. Another orifice allowed the introduction of a suctioning device. This allowed use of the T-piece principle and also provided for attachment to a Heidbrink valve and a reservoir bag for elective positive pressure ventilation. Clinically, this connection was simple to use. It aided in prevention of venous oozing, in prevention of increased intracranial pressure associated with hypercarbia and in prevention of increased resistance to respiration.

Inkster[36] studied carbon dioxide and nitrous oxide concentrations in inspired gases when using the T-piece technique. He used a mechanical "patient" and normal values from work by other investigators for respiratory rate, tidal volume and anatomical dead space. In this mechanical apparatus, rate and volume of respiration, anatomical dead space, CO_2 produced, capacity of the T-piece reservoir and fresh gas inflow were independently controlled. Since the T-piece was first designed for use in patients with normally high respiratory rates, the interval between one expiration and the next inspiration was considered to be minimal. However, results showed that as the expiratory pause was increased the percentage of CO_2 inspired decreased. When the fresh gas flow was less than twice the minute volume, the CO_2 content of the inspired gas and the extent to which the anesthetic mixture was diluted depended on the capacity of the reservoir of the T-piece and the minute volume of the patient. More significant alteration in inspired CO_2 concentration resulted when the minute volume was changed by altering depth of respiration rather than changing respiratory rate. Effective dead space was calculated from the values of alveolar gas samples, tidal volume and CO_2 output. No increase in dead space above the anatomical value was seen until the capacity of the reservoir tube exceeded 30% of the tidal volume. Effective dead space was dependent upon fresh gas flow, and with fresh gas inflow equal to twice the minute volume, the effective dead space was equivalent to the anatomical value only. In this situation, inspired CO_2 concentration was negligible. In simulating abnormal states with the highest reasonable production of CO_2 during spontaneous respiration, a fresh gas flow of 2.5 times the minute volume insured no significant rebreathing or dilution of anesthetic gases. In adults using a 120 ml capacity reservoir tube on the T-piece, a fresh gas flow equal to twice the minute volume resulted in an inspired CO_2 concentration of less than 0.05%. When the inflow was equal to the minute volume, inspired gases contained 0.8% CO_2.

Since various modifications and criticisms of the T-piece technique occurred following the first description of its use, Ayre[4] reviewed the technique with the addition of some experimental data concerning its function. He re-emphasized the simplicity of the T-tube and described the reservoir tube in more detail. The internal diameter was suggested to be 1 cm so that each inch of reservoir had a capacity of 2 ml. A larger tube of 1.25 cm internal diameter and a capacity of 3 ml/in was recommended for adults. Corrugated rubber tubing as a reservoir was not acceptable because of "increased dead space." The rate of fresh gas flow into the system was discussed, and it was noted that anesthesia without room air dilution could be achieved if the fresh gas flow was high enough. To exclude room air from the inspired gases, fresh gas flow equal to the patient's respiratory minute volume was suggested. Since the inspiratory phase of respiration was only one-third of the time for a complete respiratory cycle, the best fresh gas inflow into the T-piece was reasoned to be three times the minute volume of the patient. The addition of a reservoir tube allowed this flow to be decreased and still prevented inspiration of room air. A reservoir tube equal to one-third the patient's tidal volume allowed the fresh gas flow to be decreased to twice the minute volume. However, Ayre admitted that these figures were only approximate. Elimination of CO_2 was adequate with the reservoir volume and fresh gas flow described. The expired gases remaining in the reservoir tube were diluted due to fresh gas flow so that the ultimate CO_2 concentration was low. Clinical evidence of this function was the "quiet, effortless" breathing seen when the T-piece was used. Increased reservoir tube volume caused increased CO_2 retention. It was stated that experimental evidence indicated that fresh gas flows of 1.5-2.5 times the minute volume prevented dilution of inspired gases with room air. Also, if the reservoir tube did not exceed a volume of one-third the tidal volume, no CO_2 was present in the inspired gases. The use of the T-piece for adults undergoing neurosurgical operations was discussed. For these cases, a fresh gas flow of 12-15 l/min with a reservoir tube capacity of 150 ml was recommended to prevent room air dilution of anesthetic gases. However, a flow of 6-9 l/min with a reservoir of 72-84 ml was given to be adequate in many instances although there would be some dilution of the inspired anesthetic concentration.

Brooks *et al.*[9] superficially reviewed some of the principles and modifications of the original T-piece. The principle of application of the T-piece relied on minimal resistance to respiration and especially to expiration. T-pieces and their most common modifications, Y-pieces, of various internal diameters were examined over various fresh gas inflow rates, and the resistance was measured. Inflow rates varied from 2-50 l/min, the maximum of which was reached at normal peak respiration. The most critical factor in development of resistance appeared to be the internal diameter of the tube. Ayre's original specifications called for an internal diameter of 1 cm and any decrease in size caused rapid increase in resistance at maximum flow rates. This report indicated no justification for use of tubes with internal diameters less than 1 cm. The efficiency of Y-pieces was shown to improve due to decreased turbulence if the direction of flow was reversed from normal usage. The same relationship of internal diameter applied to Y-pieces.

Mathematical studies of the T-piece system done by Onchi *et al.*[45] gave some better guidelines for this system. They found that a flow rate three times greater than the respiratory minute volume would prevent air dilution of inspired gases without use of a reservoir tube. Also, at this flow rate dead space and rebreathing were not increased with long expiratory reservoirs. They showed that with flow rate equal to the respiratory minute volume air dilution occurred, and the inspired concentration of anesthetic mixture was 50% of that delivered. With a flow rate twice the respiratory minute volume and without a reservoir tube, air dilution occurred and the concentration of anesthetic mixture inspired was 78% of that delivered to the system. An expiratory limb with a volume of 12.5% of the tidal volume prevented appreciable dilution with room air. Also, flow rates of 5 l/min raised intrapulmonary pressure less than 5 mm of water.

Collins *et al.*[17] reviewed observations on fresh gas flow and the size of the reservoir in the T-piece system as they applied to dilution of anesthetic gases with room air and rebreathing. They stated that the fresh gas delivery tube should be directed at right angles to the endotracheal tube to prevent increases in intrabronchial and intrapulmonary pressure. Excessive flow rates resulted in increased resistance to breathing. After reviewing other studies, they concluded that a flow rate of anesthetic gases equal to twice the respiratory minute volume and a reservoir arm with a capacity of 20% of the tidal volume were clinically practical, avoiding air dilution and allowing only about 2% rebreathing of expired gases. A table consisting of gas flows and corresponding reservoir tube volumes was given.

Harrison[31] used a mechanical "patient" model to determine the fresh gas flow needed to prevent an increase in dead space in a T-piece system with a volume of 250 ml in the reservoir. Over a wide range of respiratory rate, minute volume and tidal volume, 2.0-2.3 times the minute volume was required to prevent an increase in dead space. With the pump of the mechanical "patient" adjusted for a pause at the end of expiration and inspiration, the fresh gas requirements decreased to slightly below twice the minute volume. Also, a part of the experiment used three different types of ventilators to act as constant flow generators. With rapid respiratory rates, the fresh gas flow required to prevent an increase in dead space was as high as 2.8 times the minute volume. The longer the expiratory pause the lower the fresh gas flow to minute volume ratio required. The fresh gas flow required to prevent rebreathing in a T-piece system was shown to be related to the respiratory flow pattern in both spontaneous and intermittent positive pressure ventilation. Rebreathing of expired gases was always avoided by using a fresh gas flow equal to the peak inspiratory flow rate, but this was often extravagantly high. During the expiratory pause, fresh gas traveled down the expiratory limb making a reservoir of fresh gas for inspiration if the inspiratory peak flow rate exceeded the flow rate of fresh gas. The composition of gases from the expiratory limb depended on the pattern of flow during inspiration and expiration. If the expiratory flow decreased toward the end of expiration or if there was a pause, the gases at the T-piece end of the reservoir were more of a mixture of fresh and expired gases. With a slow flow of gases into the respiratory tract at the onset of inspiration, the fresh gas continued to push expired gas out of the reservoir tube. Therefore, as respiratory flow increased, there was a greater supply of fresh gas in the reservoir than with rapid, early inspiratory flow rates. It was suggested that fresh gas flow did not need to be as high as three times the minute volume in young children. However, artificial ventilators provided more complex flow patterns requiring up to three times the minute volume to prevent rebreathing. Dead space in this experiment was calculated as follows:

$$V_D = V_T - \frac{VCO_2}{F_{ACO_2}} \times f$$

where V_D = dead space, V_T = tidal volume, F_{ACO_2} = fraction of CO_2 in the system (alveolar concentration), VCO_2 = volume of CO_2 added per minute and f = frequency of ventilation per minute.

Harrison[30] reviewed modifications of the original T-piece system and classified them into three general types. The first type was a T-piece without any expiratory limb, allowing dilution of anesthetic gases with room air. The second type had an expiratory limb capacity greater than the patient's tidal volume precluding inspiration of room air. The third type had an expiratory limb with a volume less than the patient's tidal volume allowing inspiration of room air under certain conditions. The latter two types allowed positive pressure ventilation by either occluding the end of the expiratory tube or by squeezing a reservoir bag. With type 1 during spontaneous respiration, a fresh gas flow of five times the minute volume was required to avoid air dilution. With a flow of 2.5 times the minute volume, approximately 25% of the inspired mixture was air. During controlled respiration, neither rebreathing nor air dilution occurred at any flow rate. In type 2 modifications, air dilution of the anesthetic mixture did not occur, and 2.5-3.0 times the minute volume was the flow required to prevent rebreathing during spontaneous respiration with respiratory flow patterns that occur in babies and young children. The use of this size reservoir did not increase the amount of rebreathing since CO_2 collects at the distal end of the reservoir tube. During controlled respiration, rebreathing did not occur. In the type 3 modifications, many features of the first two types were present. The amount of rebreathing during spontaneous respiration depended on total fresh gas flow and on the capacity of the reservoir tube. An advantage of the short expiratory limb was that rebreathing was limited if no bag was on the limb. Controlled respiration did not allow rebreathing or room air dilution. Resistance to respiration was similar in all types and increased only when the reservoir bag became distended. An expiratory orifice of at least 10 mm diameter was recommended.

Nightingale *et al.*[43] reported on observations on anesthetized children using system D described by Mapleson,[41] but the T-piece system described by Rees[52] was expected to behave in a similar manner with respect to fresh gas inflow requirements. The purpose of the clinical study was to establish a relationship between the size of the patient, the rate of fresh gas flow into the system and the level of the end-expired CO_2 concentration (sampled at the distal end of the endotracheal tube). End-expired CO_2 was maintained within normal limits (less than 5.2 volume per cent) at fresh gas flows more than half but less than equal to the minute volume administered by controlled ventilation. End-expired CO_2 concentration tended to decrease as minute ventilation decreased. For a constant fresh gas inflow based on body weight, smaller patients tended to have higher concentrations of end-expired CO_2 but not necessarily above normal. In all cases, end-expired CO_2 was higher at more rapid rates of ventilation despite increased respiratory minute volume and airway pressure. The observations in this study were used to show that it is only necessary to prevent excessive CO_2 retention and not total rebreathing for the modified T-piece to be practical. In manually ventilated paralyzed patients, CO_2 in the inspired gas mixture helped prevent depletion of CO_2 body stores due to hyperventilation. Respiratory rates of 20-60 bpm were recommended for controlled ventilation with this system. Total gas flow rates of 3 l/min for children under 30 lbs and 100 ml/lb/min for larger children were suggested to prevent CO_2 retention.

Sykes[67] reviewed rebreathing in various anesthetic circuits. His conclusion was that elimination of CO_2 from semiclosed circuits without absorbers depended upon fresh gas flow, tidal volume and pattern of breathing. Circuits without separations between fresh gas, dead space gas and alveolar gas proved less efficient. In the Ayre's T-piece system with the expiratory limb containing a volume greater than the animal's tidal volume, dilution of gas with room air seemed unlikely. Rebreathing did not occur if fresh gas flow exceeded peak inspiratory flow, but a smaller fresh gas flow was used in most circumstances without rebreathing. A high inspiratory:expiratory time ratio, a slow rise in inspiratory flow rate, a low flow rate during the end of expiration and a long expiratory pause reduced the chance of rebreathing with an Ayre's T. A fresh gas flow of 2.0-2.5 times the minute volume was recommended to eliminate rebreathing.

Baraka[5] measured arterial P_{CO_2} levels at various fresh gas inflow rates using a Mapleson D semiopen system with ventilation controlled at a constant minute volume of 16 l/min. He found that at normal body temperature normocarbia was achieved at a fresh gas inflow of 5 l/min which was approximately equal to the alveolar ventilation volume of the average adult. The P_{CO_2} obtained was inversely proportional to the fresh gas flow.

Pediatric Anesthesia and the Pediatric Circle

Stephen and Slater[66] reviewed anesthetic agents and techniques employed in human pediatric anesthesia. They concluded that size made children more difficult candidates for anesthesia while gas machines and technical equipment were primarily designed for adults. They stated that it was harmful to anesthetize a three-year-old child with nitrous oxide and ether via an adult circle absorption gas machine, but that nonrebreathing techniques were useful without physiologic upset. The ideal technique was described as one that offered no resistance to respiration, had no mechanical dead space, permitted no accumulation of CO_2, allowed rapid change of depth of anesthesia and provided artificial ventilation. Various techniques involving masks were described. The adult circle absorption system was not recommended for children under six years of age because of resistance and mechanical dead space. Endotracheal techniques were advised in any situation of compromised airway. The use of Ayre's T-tube was noted and hailed for its lack of resistance, lack of dead space and removal of CO_2, but was considered "not physiologic" because of being a constant insufflation anesthesia technique. The authors recommended use of a nonrebreathing valve for pediatric anesthesia.

Andriani and Griggs[1] published recommendations and descriptions of improvements in rebreathing apparatus for pediatric anesthesia. They stated that use of a standard adult rebreathing circle in infants resulted in anesthesia that was not "smooth", in laborious respiration suggesting hypercapnia and in difficult induction. These problems were related to excessive dead space, inefficient CO_2 absorption, resistance to gas flow and inadequate mixing of gases and vapors. The premise that children are just small people and therefore require small apparatus was rejected. Also, a need for standardization of fittings, tubing, valves and canisters was expressed. Then, the problems listed were attacked and at least partially solved by certain modifications of a standard adult circle system. The to-and-fro rebreathing system was not recommended because of positioning of the canister, variation of dead space as the absorbent was used and impracticality of changing canisters frequently during pediatric anesthesia. The dead space of the standard Y-connector for breathing hoses in an adult circle was eliminated by a connector designed as a tube within a tube. The internal tube and its valve allowed inflow of gases unidirectionally, and the external tube allowed outflow of gases unidirectionally. Therefore, the only dead space remaining was in the mask, and this was handled partially by providing a variety of masks for various sized patients. However, the main improvement in the mask was the attachment of a manually operated pump to allow removal of gas in the mask to the rebreathing bag as often as the anesthesiologist deemed necessary. Breathing tubes and fittings remained the standard size because of low resistance and almost universal application. The design of valves was also considered to prevent increased resistance and "backlash" (regurgitation of gases before the valve shut). The valves selected had an aperture greater than that of a 39 French endotracheal tube to decrease resistance. They were made of semirigid rubber 1 mm thick and attached on a brass bushing with a 1.4 cm aperture in a hinge-like manner. These were low in resistance, and with tidal volumes less than 200 ml backlash was eliminated. The standard 5 1 rebreathing bag was discarded for pediatric use because of low tidal volume making respiratory movements difficult to see and because size and stiffness of the bag could lead to increased expiratory resistance. Also, when filled completely, such a bag often imposed a pressure of 5 cm of H_2O. Therefore, use of 500-1500 ml thin latex bags was recommended. These designs were made to be adaptable to a standard circle system and to be used as either a closed or semiclosed system for children under 8 to 9 years of age. However, the design had not been clinically tested for premature infants at the time of the article.

Voss[69] studied the effective apparatus dead space of the Magill, Potter and Cape Town (a modified T-piece) gas circuits using a model "patient" system simulating 3- and 8-year-old children. The dead space was evaluated by considering the use of a mask rather than an endotracheal tube. The Potter system and the Cape Town system for decreasing dead space were compared to the Magill system. These comparisons were made because increased dead space had been shown to change ventilation and the value of respiratory variables by Clappison and Hamilton.[15] The systems were evaluated at fresh gas flows of 4 and 8 l/min with constant minute volumes, respiratory rates, tidal volumes and CO_2 production. The results showed total dead space and alveolar CO_2 percentage to be less in the Potter and Cape Town systems. The Cape Town system was recommended for smaller children due to absence of valves and lower resistance. However, the Potter system had lower dead space values at lower flow rates in the older subjects making it more economical.

Cullen[19] described a pediatric circle absorber developed by Dr. Edward R. Bloomquist, Los Angeles, California. The instrument consisted of a canister, directional valves, breathing bag and tubes and standard connectors and adapters. It utilized a 5 in square metal base to stabilize the canister. Two parallel horizontal 5/8 in channels traversed the base. Two vertical channels connected with the previously mentioned ones to allow connection to the canister and completion of the circle. Breathing hoses attached to two holes in the base, and the other two holes were stopped by a rebreathing bag and a rubber plug. The choice of directional valves was described as optional and included the Digby Leigh filter, the Sierra Y-valve or a modified Edison Y-valve. The positioning of the bag and the direction of gas flow were modified to suit the needs of the anesthesiologist. If the canister was placed in the path of inspiration, its resistance was overcome by assisting the infant on inspiration, but this advantage did not exist if the canister was on the expiratory side of the circle. The equipment was suggested to be very versatile, and was designed to be a simple, compact, trouble-free unit with a soda lime absorber for maximum efficiency.

Hoffer[34] described the use of a closed system utilizing a pediatric circle for the administration of halothane to small animals. However, the apparatus described was also usable as a semiclosed system. The apparatus consisted of an oxygen source, flow meters, vaporizer, a Bloomquist infant circle absorber including 15 mm adapeters and connectors, a rebreathing bag and breathing tubes, and a Sierra Y-piece with expiratory valve. Recommended flow rates for the system were not provided. A description of the technique for halothane-oxygen anesthesia for small animals was given, and this technique was recommended for critical cases and small patients. This anesthetic system was not compared with other systems, and advantages of the system except for economy were not noted.

Rackow and Salanitre[49] reviewed many aspects of pediatric anesthesiology. Among other subjects, they discussed apparatus, techniques and respiration in infant anesthesia. Various articles concerning the Ayre's T-piece and its modifications were reviewed, and conclusions were made. Any T-piece system used required high gas flows and gave rise to problems of respiratory humidification. Resistance was minimal with the T-piece. The use of the adult circle system had been generally avoided for infants and children based upon increased air-flow resistance. However, the report noted that quietly breathing infants had inspiratory and expiratory flow rates that averaged 2-3 l/min reaching a maximum of 6-9 l/min during crying, and these flows did not result in significant resistance in the circle. Since resistance was reported to increase exponentially with flow, larger patients had greater resistance due to greater flow. Respiratory efforts by infants on adult circle systems were shown to be greater than infants on the Ayre's T-piece system or infant circle systems. Increased effort was correlated to increased dead space of the system. The conclusion was that circle systems could be used for all pediatric age groups if total dead space, air-flow resistance and opening pressure of the valve system were small. Columbia, Bloomquist and Ohio pediatric circle systems were mentioned. Advantages of these circles included ease of assisting ventilation, convenience and safety for all age groups, humidification of gases without additional equipment and the use of several anesthetic gases at low flow rates. Increased flow rates in children on circle systems caused the systems to functionally approach nonrebreathing systems and caused a decreased humidification of gases.

In spontaneously-breathing infants during endotracheal halothane anesthesia, it has been shown that 5-15 min after intubation, the P_aCO_2 increased from 34-46 mm Hg. Two hours later, the P_aCO_2 was relatively unchanged at 43 mm Hg. In this study, Podlesch *et al.*[48] utilized various types of anesthetic systems. The evidence suggested that the spontaneously-breathing normal infant achieved physiologic levels of ventilation with a variety of anesthetics and anesthetic systems. Assisted or controlled respiration was recommended.

Adult Circle CO_2 Absorption Systems

Hunt[35] described the general principles of air flow at a steady state in ducts and then provided experimental verification of the principles of flow past disc type valves and through CO_2 absorption canisters. The effect of intermittent and pulsating flow past disc type valves was shown experimentally. The influence of humidity on valve behavior was also discussed. He concluded that disc type valves should be as light as possible, should have a lift of one-fourth the diameter of the duct and have approximately the same cross-sectional flow area as the constricted portions of the duct. Spring loading of valves was not recommended. Also, soda lime in standard absorption canisters was incriminated to impose more resistance to flow than disc valves (except at very low velocities) especially if soda lime granules were small. Therefore, short wide canisters and large granules of soda lime were suggested. Humidity in air did not produce a noticeable effect on valves unless the undersides became coated with water. Then, air flow had to overcome surface tension of the water between the valve and the valve seat. This amount of resistance appeared to the author to be negligible during clinical anesthesia.

Orkin *et al.*[46] studied resistance to breathing in apparatus used in anesthesia at flow rates of 8-95 l/min. In all instances, the CO_2 absorption canister accounted for 10-15% of the expiratory resistance. All machines and valves were tested using dry oxygen. It was noted that with older type Foregger dome valves the weight of the valve and the housing of the valve contributed equally to the resistance imposed. Overflow or "pop-off" valves were found to operate satisfactorily only at flow rates less than 10 l/min. With various circle anesthetic systems, directional valves were always present causing increased resistance to both inspiration and expiration. Valves had about the same resistance whether located at the Y-piece or between the breathing hoses and the canister. Tubing and canister had about the same resistance and contributed together about one-third of the total expiratory resistance. The effects of valves altered normal physiology. Resistance to valves was smaller at low flow rates (those used for children) than at high flow rates (those used for adults).

Eger and Ethans[24] examined the effects of valve placement, rate of fresh gas inflow, overflow valve placement, dead space, tidal volume and alveolar ventilation on the economy of the circle anesthetic system. A simulated "lung" driven by a Harvard pump to deliver a sine-wave ventilatory flow pattern was used in the experiment. A CO_2 inflow of 200 ml/min simulated CO_2 elimination. In general, placement of the overflow valve near the patient was most economical. Increasing alveolar ventilation decreased economy regardless of overflow placement. When the overflow was placed away from the patient (not at the Y-piece), increasing dead space and tidal volume to maintain constant alveolar ventilation decreased the economy. No change was noted with the overflow at the Y-piece. Controlled ventilation did not change economy if the overflow was not at the patient, but it decreased economy if the overflow was at the Y. The most economical arrangement under all circumstances placed inspiratory and expiratory valves at the Y-piece connection to the patient with the overflow located just downstream to the expiratory valve. At any given rate of fresh gas inflow, the most economical system retained gases containing the greatest concentration of anesthetic agent and the lowest concentration of CO_2.

Brown *et al.*[11] studied CO_2 elimination in semiclosed circle systems using a mechanical ventilation model with standard test conditions including a 500 ml tidal volume, 150 ml of dead space, 16 respirations/min, 284 ml/min of CO_2 production and 90% relative humidity at 30 C in "expired air" at the "mouth." With spontaneous breathing the most efficient use of soda lime was an arrangement with the overflow valve in the Y-piece connecting the breathing hoses. The site of the reservoir bag or the location of the valves did not affect the life of the absorbent. When the fresh gas inflow was located on the inspiratory limb rather than between the CO_2 absorber and the inspiratory valve, the life of the absorbent was halved. During controlled breathing the poorest lime efficiency was with the overflow valve located in the Y-piece. It was more efficient with the controlled breathing to have the bag on the expiratory side of the circle. No difference in absorber efficiency was found during spontaneous ventilation with the use of valves located at the Y rather than at the absorber. However, valves at the Y were more efficient during controlled ventilation. To use a circle system for both spontaneous and controlled ventilation, valves located at the Y, the reservoir and overflow on the expiratory side and the fresh gas inlet on the inspiratory side proved more efficient. During spontaneous ventilation, alveolar air was discarded from the system if the overflow was at the patient or on the expiratory side. Admixture with fresh gas was prevented by placing the fresh gas inflow between the absorber and the inspiratory valve, and the positioning of the bag or valves was not critical. Controlled ventilation was less efficient in prolonging absorber life than was spontaneous respiration. A Georgia valve was no more efficient in conserving absorbent than was the spring-loaded overflow valve. Regardless of the component arrangement, the semiclosed system did not produce economy with respect to the usage of anesthetic gases. The advantage of a semiclosed system was that incresing inflow to equal the minute volume yielded essentially a nonrebreathing system in which only fresh gas entered the lungs. However, to produce total nonrebreathing, flows greater than the minute volume were required.

Comparison of Anesthetic Systems

Stephen[65] described the use of a nonrebreathing technique for anesthesia in babies and compared it clinically to other techniques. First noted were the fundamental problems involved in anesthesia in children related to anatomic structures involved. Small airways, underdeveloped intercostal muscles and small volume of gas exchange were three factors listed. Tidal volume decrease was related also to obstruction, depressant agents, muscular fatigue and rapid shallow respirations leading to rapidly altered physiology. The narrow margin of error in anesthesia for children was related to the small residual volume of the lungs. Therefore, anesthetic techniques for infants and children needed to be more exacting. Obstruction of the airway leading to anoxia, mechanical dead space decreasing gas exchange, accumulation of CO_2 related to dead space and depressed respiration, and resistance within the anesthetic apparatus were listed as factors to be minimized in anesthetized children. Dead space, lack of a method of positive pressure ventilation, CO_2 accumulation and low oxygen tension were described as shortcomings of the open drop technique of anesthetic administration. Total rebreathing circle systems for children under 8 years were not recommended unless respiration was assisted throughout the anesthesia period. To-and-fro systems were described as useful for children older than 2 years if soda-lime canisters were changed frequently. The Ayre's or insufflation technique was praised for its lack of resistance to respiration and negligible dead space. However, constant insufflation was called "not physiologic" with increased retention of CO_2. A reservoir for assisting respiration was not present with the Ayre's method examined. The technique recommended for children utilized a nonrebreathing valve with rubber flaps for control of direction of gas flow. At flows of 15 l/min, resistance to expiration was only 1 cm of H_2O. Dead space was only about 9 ml which was not more than the mouth of an infant. Also, a reservoir bag was present for assisting or controlling ventilation. This system satisfied the demands of pediatric anesthesia.

Woolmer and Lind[70] studied the elimination of CO_2 by the Magill system, a simple T-piece and a Bullough system using a mechanical laboratory model. A respiratory rate of 16/min, a tidal volume of 400 ml, a minute volume of 6.4 l/min, a dead space of 150 ml and a CO_2 input of 14 ml/"breath" (to achieve 5.6%) were maintained for each system under study. In the Magill system, the CO_2 was 0.12% at 7 l/min flow, and CO_2 percentage increased with decreasing fresh gas flow. The T-piece system had 1.3% CO_2 at 10 l/min and 2.7% at 7 l/min. Bullough's arrangement had a CO_2 percentage between the other systems at comparable flow rates. When tidal volume was increased to 500 ml and 700 ml at flows of 5 l/min and 7 l/min of fresh gas flow, CO_2 rebreathed increased in the Magill system, slightly increased in the Bullough system, and did not increase in the T-piece system due to dilution of the inspired gas with room air. The T-piece system was called inferior for eliminating CO_2. However, the constants used simulated an adult, and the T-piece was not recommended for use in adults by the original work.

Mapleson[41] studied the effects of the expiratory valve, reservoir bag and breathing patterns in several semiclosed anesthetic systems by use of mathematical theories. The fifth system studied, comparable to an Ayre's T-piece since it had no valves, was found to be less economical than other systems because of high gas flows needed to prevent rebreathing. However, this system supplied less resistance to respiration especially at high flow rates due to absence of an expiratory valve. Rebreathing was eliminated with fresh gas flows equal to twice the minute volume or lower if there was an expiratory pause.

Graff *et al.*[27] studied the alteration of acid-base values in 2-week-old to 7-month-old infants receiving halothane anesthesia by means of an adult circle-absorption system. A Y-piece insufflation technique was used as a control to minimize external dead space and resistance. Induction was with nitrous oxide, halothane and oxygen followed by endotracheal intubation. Maintenance of anesthesia was divided into four 15-minute periods in which the system was altered between the insufflation method and the adult semiclosed circle with unidirectional valves in the connector of the breathing tubes. Six infants were maintained in light planes of anesthesia, one in a moderately deep plane and one in a deep plane. Blood pressure, pulse and body temperature were maintained reasonably constant. The two infants in deeper planes of anesthesia developed respiratory acidosis, but not much change in bicarbonate levels was noted. Therefore, metabolic acidosis was not considered to be a factor. Average values for pH and PCO_2 were not significantly different for the two systems. The conclusions were that with relatively high gas flows and with unidirectional valves near the endotracheal catheter, the use of an adult circle-absorption system offered a safe and physiologic technique for administering anesthesia to patients of all age groups. The authors related that the peak inspiratory flow rate of a 3-month-old infant was 6 l/min and 9 l/min for a 9-month-old infant. At these flows, adult size soda-lime canisters, breathing tubes and valves offered negligible resistance as shown by Orkin[46] and Hunt.[35] The dead space and resistance of the unidirectional Y-piece valve were nullified by use of endotracheal intubation and by use of unspecified high flow rates.

Ver Steeg and Stevens[68] questioned the normal values for acid-base balance obtained by Graff *et al.*[27] for infants maintained on adult circle systems. Therefore they compared the respiratory effort expended by infants maintained on several adult and pediatric anesthetic circuits. Infants under 1 year of age anesthetized with halothane-nitrous oxide-oxygen or halothane-oxygen were studied following a surgical procedure. A pneumotachograph was imposed between the endotracheal tube and the system, and airway pressure was monitored. Inspiratory negative pressure was used as an indicator of effort required to move the inspiratory volume. An index of inspiratory effort was calculated by dividing inspiratory volume (ml) by the area of the inspiratory pressure trace (sq mm). Systems compared included a T-piece (6.22 mm i.d.), two infant circle absorber systems and adult circle systems with various types of dome valves, the Ohio swivel valve, and the Sierra Y-headpiece valve. The T-piece and the infant circle systems were notably more efficient than the system with the Sierra valve and somewhat more efficient than the system with the Ohio swivel. With one exception the pediatric systems were more efficient than the adult systems. The adult systems ranged between the McKesson circle which was highly efficient and the Sierra valve which was uniformly less efficient. However, volumes on inspiration were not compromised by the less efficient systems. This study gave an index of the effort required by the infant to maintain respiratory need as related to resistances in various systems.

Rebreathing and external dead space were determined in equipment for infant anesthesia by Brown and Hustead.[10] A model "patient" was used for the study. Use of masks increased external dead space as did the addition of Stephen-Slater, Digby-Leigh or Sierra valves. The Ohio Swivel-Y-valve increased external dead space to more than 19 ml. The Norman elbow, the Foregger mask elbow, the Ohio Infant Circle and the Stephen nonrebreathing mask reduced dead space under the mask at flows of 3 l/min. With this flow rate and endotracheal intubation, the Stephen-Slater, Digby-Leigh, Norman elbow, Ayre's "T" and Ohio Infant Circle systems showed no rebreathing. Valved systems improved in performance with larger tidal volumes, and open systems required larger flows. Open systems with adequate inflow were recommended for premature infants, but the adult circle with valve-in-chimney was considered marginal for such a patient.

Soma[62] described the use of the Ayre's Y-piece as a semiopen method of delivering anesthetic agents to veterinary patients, especially small dogs and cats (under 4.5-5.4 kg). Advantages of this system included low resistance to respiration, simple design and rapid control of the delivered concentration of anesthetic agent. To prevent rebreathing of exhaled gases, the rate of oxygen flow was recommended to be greater than the patient's respiratory minute volume, allowing flushing of the expiratory limb with fresh gas. The addition of a reservoir tube decreased dilution of the oxygen-anesthetic mixture with room air and this reservoir was recommended to have a volume approximately equal to one-third of the animal's tidal volume. He suggested a fresh gas inflow of 2.5 times the respiratory minute volume to assure proper flushing of CO_2 from the expiratory limb. Soma also suggested a flow of three times the respiratory minute volume to prevent rebreathing if the Ayre's system was modified by the addition of a rebreathing bag. This technique was recommended for animals under 5.4 kg since larger animals required higher gas flows creating resistance to respiration in the narrow diameter of the Y-piece. Nonrebreathing techniques utilizing valves were also described. Soma described semiclosed rebreathing systems in which part of the animal's exhaled gases were passed back into the system and part escaped into the atmosphere. The amount of fresh gas inflow into the system determined the amount of used gas that was rebreathed, making it necessary to give the flow rate used when describing a semiclosed system. Circle systems were also discussed. The use of high oxygen flows caused a semiclosed circle to approach functionally a nonrebreathing system. Soma stated that unidirectional valves created most of the resistance in the circuit, and dome valves were preferred. Breathing tubes with diameters of 1.9 cm (designed for pediatric usage) were recommended. Soma also described various brand names of vaporizers. The vaporizer out-of-the-circle was related to be more practical and safer than the in-the-circle type. Soma recommended higher flow rates for induction and lower flow for maintenance.

Short[60] compared closed, semiclosed and nonrebreathing systems in horses anesthetized using halothane. His conclusions were based on analyses of heart rates, blood pressures, electrocardiograms, minute and tidal volumes, blood gases, pH and recovery responses. The conclusions reached and data collected supported the view that nonrebreathing systems are the safest. Arterial PCO_2 and pH were closer to control values in animals maintained on nonrebreathing systems. Blood pressures and heart rate were lower in horses on nonrebreathing systems, but the author felt that this was due to a deeper plane of anesthesia.

Hartsfield and Sawyer[32] compared the T-piece system and the semiclosed circle system for maintaining halothane-oxygen anesthesia in cats. They found that animals maintained on the T-piece system were more stable, had higher arterial pH, lower arterial PCO_2, lower respiratory rates, higher heart rates and arterial pressures and had less base deficit. The conclusions reached were that the T-piece system was more convenient to use for cats, provided more stable maintenance anesthesia for small patients, and yielded more acceptable values for the cardiovascular variables measured.

Alveolar Ventilation at Low Tidal Volume

Briscoe *et al.*,[8] using five normal human subjects, studied the degree of alveolar ventilation at very low tidal volumes. They wanted to show that a sharp boundary was not maintained between the alveolar gas and dead space gas but that dead space gas was penetrated by a cone-front. They studied this by using helium, an insoluble foreign gas. This study showed that after inspiration of as little as 60 ml of 80% helium-20% oxygen, detectable quantities of helium were in the alveolar gas. Since the anatomical dead space of the subjects was near 150 cc, the inspired air probably penetrated dead space gas first in the center of the airway leaving the dead space gas on the periphery relatively undisturbed. Inspired volumes of 10–30 ml did not allow helium detection in the alveoli. Therefore, the formula stating that alveolar ventilation equals tidal volume minus dead space volume is incorrect unless the tidal volume is large enough to completely flush the dead space volume.

External Dead Space in Anesthetic Systems

Clappison and Hamilton[15] studied the quantitative aspects of respiratory adjustments by man to relatively small increases in external dead space. Tidal volume, minute volume and expired CO_2 concentrations were measured for control values, for an external dead space of 40 ml and for an external dead space of 165 ml. With the addition of dead space, tidal volume and expired CO_2 both increased, but the increase in tidal volume was less than the amount of added dead space. Minute volume also increased but less than the increase in dead space minute volume. This was related to increased end-expiratory CO_2 concentration. The authors concluded that small increases in dead space such as that found in anesthetic equipment, inhalation therapy apparatus and devices for measuring respiratory function were of significance even in normal subjects who were able to partially compensate. This dead space was given more importance in disease states and in states of drug depression where a patient might be unable to compensate. Changes in tidal volume, minute volume and end-expiratory CO_2 were statistically different from control values when 165 ml of dead space was added to the anatomical dead space of normal, unanesthetized human subjects.

Nunn and Hill[44] made observations on 12 human beings anesthetized for routine surgical procedures during artificial and spontaneous respiration. The mean value for the difference between arterial PCO_2 and end-tidal PCO_2 was 4.5 (S.D. = $\pm$2.5) mm Hg. They suggested that during anesthesia of normal subjects the arterial PCO_2 will be 0-10 mm Hg higher than end-tidal PCO_2 regardless of the manner or depth of respiration. The study also showed that anatomical dead space, physiological dead space and alveolar dead space increased under anesthesia.

Cardiac and Respiratory Values for Normal Cats

In a study involving 22 cats with average body weight equal to 2.5 kg under chloralase anesthesia (80 mg/kg), Bartorelli and Gerola[6] found the respiratory rate to be 15 breaths/min, the tidal volume to be 26 ml, the minute volume to be .380 l/min, and oxygen uptake to be 18.5 ml/min. Cardiac output averaged 234 ml/min by the Fick method and 184 ml/min by the Stewart-Hamilton method with considerable individual variability partially dependent on body size. Body surface area was measured directly on 12 cats, and a coefficient for prediction of body surface on a body weight basis was calculated to be $m^2 = 0.087\ kg^{2/3}$.

Herbert and Mitchell[33] studied blood gas tensions and acid-base balance in awake unrestrained cats with catheters implanted chronically in the aorta and vena cava. The average arterial pH was 7.426, the average venous pH was 7.363, P_aCO_2 averaged 32.5 mm Hg, P_vCO_2 averaged 40.8 mm Hg, arterial HCO_3^- was 21 mEq/l, venous HCO_3^- was 22.4 mEq/l, P_aO_2 averaged 107.6 mm Hg and P_vO_2 averaged 39.1 mm Hg. Mean arterial O_2 saturation was 97%. The average rectal temperature was found to be 38.9 C. A metabolic acidosis with pH ranging from 7.304 to 7.373 was seen for up to 7 days in cats after surgical implantation of catheters.

Therefore, none of their data was collected during the first postsurgical week.

Fink and Schoolman[26] reported P_aCO_2 to be 28 mm Hg, pH to be 7.38 and HCO_3^- to be 16.06 mEq/l in awake cats.

Another study by Sorensen[64] showed a P_aCO_2 of 29.9 mm Hg at 37 C which correlated well with the study by Herbert and Mitchell[33] when corrections were made for temperature differences.

Halothane Anesthesia

The action of halothane in cats has been studied and described by various workers. Raventos[50] reported that during anesthetic induction with 2.0 to 4.0% halothane vapor, blood pressure decreased from 130 mm Hg to 90 mm Hg in dogs, and he also reported a greater change for cats and rabbits. Beaton[7] studied the effects of halothane in cats and reported a definite bradycardia without reduction in stroke volume. Cardiac output was reported to be further decreased with increasing concentrations of halothane. Direct depression of the myocardium was reported at halothane concentrations greater than 2%, and total peripheral resistance decreased at concentrations greater than 0.5%. The conclusions from this study were that there was hypotension due to action on both the myocardium and arterioles. Burn and Epstein[12] reported a relaxing effect on the smooth muscle of vessels, spleen, and intestine. The conclusion was that halothane decreased blood pressure partly by its effect on smooth muscle. Raventos[51] studied the effects of halothane on the autonomic nervous system of cats and concluded that hypotension during halothane anesthesia was due to depressant action on the autonomic ganglia or possibly due to action on the vasomotor center. Payne and Plantevin[47] studied cardiovascular effects of halothane in cats reporting bradycardia which was correctable with atropine and hypotension due to peripheral vasodilation. They also reported vasoconstriction with small concentrations of halothane.

Sawyer[55] studied the cardiovascular effects of anesthetics in chronically implanted miniature swine and reported on the effects of halothane. This study eliminated the effects of premedication and gave an account of cardiovascular changes that could be expected. Cardiac output decreased 50%, mean arterial pressure decreased 44% and stroke volume decreased 50%. Heart rate did not change significantly. Peripheral vascular resistance increased 12-17%. P_aCO_2 and P_aO_2 and oxygen saturation of arterial blood increased, and there was a decrease in arterial pH.

Summary

The Ayre's T-piece, a system first recommended for use in pediatric anesthesia, has been evaluated by a number of investigators. Ayre[3] first stated that the tube should have an internal diamter of 1 cm to achieve the positive effects that he described in babies. Brooks[9] later stated that the internal diameter was critical and that it should not be less than 1 cm. Another report by Collins[17] stated that the fresh gas inflow should always be at right angles to the tube to prevent increases in intrabronchial and intrapulmonary pressures. The fresh gas flow required by the T-piece system has been a matter of conjecture. Ayre[3] first recommended a total flow of 1.5-2.0 l/min. With the use of a reservoir tube, Inkster[36] suggested that a flow equal to twice the minute volume of the patient would prevent any increase in dead space. However, Ayre[4] restated the necessary flow saying that three times the minute ventilation should be used to exclude room air.

Onchi[45] strengthened this by showing mathematically that there was no room air dilution of anesthetic gases using a T-piece without a reservoir tube if the total fresh gas flow was equal to three times the minute volume, but he suggested lower flows to be more applicable with the use of reservoirs. Harrison[30] suggested the use of a flow equal to 2.0-2.3 times the minute volume to prevent increases in dead space. However, he stated that this could be lowered if there were inspiratory and expiratory pauses. Finally, Sykes[67] stated that a fresh gas flow of 2.5-3.0 times the minute volume would eliminate rebreathing or dead space. Inkster[36] said that room air dilution of anesthetic gas in an Ayre's T-piece system depended on minute volume and expiratory tube capacity if the total flow was less than minute volume. The size of reservoir tube has also been questioned. Ayre[4] stated that the capacity should be one-third of the patient's tidal volume if the fresh gas flow was equal to twice the minute volume. This allowed no increase in dead space. Onchi[45] stated that increased length of the reservoir tube did not increase dead space and that a capacity of 12.5% of the tidal volume prevented appreciable room air dilution. Collins[17] recommended a flow rate of twice the minute volume and a reservoir capacity of 20% of the tidal volume. Harrison[31] further stated that the addition of a reservoir added very little resistance to the system. Baraka[5] reported rebreathing of CO_2 or increased P_aCO_2 in patients on an Ayre's T-piece system to be inversely proportional to the gas flow rate. Therefore, the consensus found little resistance and dead space imposed by the Ayre's T-piece system. Rate of fresh gas flow required depended on the capacity of the reservoir. Practically, flow rates of 2.0-3.0 times the minute volume and reservoir capacities equal to 20-30% of the tidal volume were usable.

Pediatric anesthesiology has raised various questions concerning techniques of anesthesia. The size of the child and the design of the equipment have been stated to be influences on pediatric anesthesia by Stephen and Slater.[66] They also stated that adult anesthetic systems were not good for use in children because of the dead space and resistance inherent in these systems. Andriani and Griggs[1] reported difficulty with anesthesia in children on adult circle reabsorption systems, and they suggested several modifications for the adult system to decrease the dead space and resistance. Reports by Stephen and Slater,[65] Voss[69] and Cullen[19] recommended nonrebreathing valves, modified T-piece systems, and pediatric circles for use in children in preference to standard adult circles. Hoffer[34] recommended a similar pediatric circle for use in small animals in veterinary anesthesiology. A review article by Rackow[49] on pediatric anesthesiology stated that the T-piece was preferred for pediatric anesthesia, but it also reported that adult circles did not increase resistance to gas flow in anesthetized children. The use of pediatric circles was praised because of decreased dead space, ease of gas humidification and lowered pressures for opening of valves. Finally, Podlesch[48] stated that infants and children could be anesthetized satisfactorily on a variety of systems.

Adult circle reabsorption systems have been evaluated by a number of investigators. Hunt[35] showed that disc valves should be as light as possible and have a lift of one-fourth the diameter of the duct. Another study by Orkin *et al.*[46] reported that unidirectional valves imposed equal resistance no matter where they were located in the circle and that they did alter normal physiology. The same group stated that valvular resistance to air flow was less at lower flow rates. Eger and Ethans[24] showed that placement of the unidirectional valves near or at the Y-piece with the overflow valve just downstream on the expiratory side and fresh gas flow on the inspiratory side was the most efficient in CO_2 removal and use of soda lime. For overflow valves, Hunt[35] did not recommend spring-loading. The placement of this valve at the Y-piece has been shown to be most economical with respect to soda lime utilization during spontaneous ventilation by Brown and Hustead[10] and by Eger and Ethans,[24] but this was reversed if controlled ventilation was used. With the circle, economy decreased with controlled ventilation. With a semiclosed circle, Brown and Hustead[10] showed less economy in any arrangement of valves and overflows with respect to anesthetic utilization as compared to a closed system. The effects of soda lime canisters have also been studied, and Orkin *et al.*[46] reported them to impose 10-15% of the resistance to expiration in an adult circle system. Hunt[35] reported canisters to impose more resistance in a circle than valves, and the use of larger soda lime granules was recommended to decrease resistance. Efficiency of soda lime utilization has been shown by Eger and Ethans[24] to increase as fresh gas flow increased and to decrease as alveolar ventilation increased. Both decreased the economy of anesthetic utilization. The breathing hoses also increase resistance in a circle system, and Orkin *et al.*[46] indicated that tubing and canisters supplied one-third of the resistance to air flow in a circle. A final consideration was the presence of water vapor which Hunt[35] reported to be unimportant as related to total resistance unless the valve seat and valve became completely water coated.

Several reports have compared the use of various anesthetic systems. Stephen[65] did not recommend total rebreathing systems for children under 8 years of age unless respiration was assisted throughout anesthesia. This was stated due to resistance and dead space of the systems and to the smaller anatomical structures and volumes in children of this age group. The Ayre's technique was praised due to low resistance and dead space but was called "not physiologic." However, a nonrebreathing valve with a reservoir bag was described as most useful for producing physiologic pediatric anesthesia. Woolmer and Lind,[70] comparing three systems using adult flow rates, reported the T-piece to be inferior for eliminating CO_2, and it was not recommended for use in adults. Another comparative study by Mapleson[41] found a system similar to the Ayre's T-piece to be less economical due to flow rates required but to supply less resistance due to absence of an expiratory valve. Comparative acid-base measurements by Graff *et al.*[27] in patients rotated every 15 minutes between an adult circle system and an insufflation system showed no significant differences. However, Ver Steeg and Stevens[68] measured respiratory effort expended by infants maintained on various anesthetic systems. In general, pediatric circle systems required less respiratory effort than adult systems. The T-piece system was comparable to the pediatric circle systems tested. The Sierra Y-valve was employed in some circles and proved to be the least efficient. Another study by Brown and Hustead[10] measuring rebreathing and external dead space of various systems, recommended open systems with adequate inflow for premature infants, but the adult circle with the valves located at the Y-piece was considered marginal for such patients. For veterinary anesthesia, Soma[62] recommended the Ayre's method for small dogs and cats due to simplicity, low resistance and dead space and control of the inspired anesthetic concentration. Another study in horses by Short[60] concluded that nonrebreathing systems were safest and least economical. Finally, Hartsfield and Sawyer[32] compared the T-piece to the semiclosed circle system for cats and reported the T-piece to produce anesthesia that was clinically and physiologically more acceptable.

<u>External dead space</u> due to anesthetic systems was reported by Clappison and Hamilton[15] to be of most importance in patients with compromised respiratory function because end-expiratory CO_2 values increased in normal patients when 165 ml of dead space was added. Also, Nunn and Hill[44] reported that anatomical, physiological and alveolar dead space increased during anesthesia.

<u>Normal cardiac and respiratory values for cats</u> have been reported by various researchers including Bartorelli and Gerola,[6] Herbert and Mitchell[33] and Fink and Schoolman.[26] These varied with technique, duration of study and condition of the animals.

<u>The cardiovascular effects of halothane</u> have been studied and summarized by Sawyer[55] through an extensive literature review and research. In general, cardiac output, stroke volume and mean arterial pressure decreased as did arterial pH. P_aCO_2 increased as did peripheral resistance. Heart rate remained unchanged or decreased.

MATERIALS AND METHODS

Animals and Conditioning

Eighteen domestic shorthair cats (*Felis domestica*) were utilized in this study. These animals were mature but not of advanced age and ranged in body weight from 2.5 to 4.3 kg. Housing consisted of individual concrete cages in accordance with Public Law 89-544 (The Animal Welfare Act). Cages were cleaned twice daily. Animals were exercised and fed once daily and received water *ad libitum*. The cats were vaccinated against feline panleukopenia upon arrival, and fecal examinations for internal parasites were performed. Animals received physical examinations, were treated for internal parasites and were maintained for at least 30 days prior to catheter implantation. No drugs were administered for at least two weeks prior to catheter implantation. After implantation and before study, each animal was handled periodically to decrease some apprehension on the day of study. Immediately before control measurements were taken on the day of study, a 3 ml venous blood sample was drawn from a jugular vein catheter for complete blood count, blood urea nitrogen determination (BUN) and serum glutamic pyruvic transaminase (SGPT) test to determine clinical normalcy in each animal on the day of study. Tests were performed at the Veterinary Clinical Pathology Laboratory, Michigan State University.

Materials

The silicone rubber tubing[a] (0.040 in ID x 0.085 in OD) to be placed in the jugular vein was attached to a blunted 15 gauge hypodermic needle (Figure 1) to allow adaptation of a three-way stopcock[b] (Figure 2). This catheter was used for blood sampling, monitoring venous pressure and injecting room temperature saline during cardiac output determinations. An 18 gauge polyethylene catheter[c] (0.034 in ID x 2.75 in) was placed in a femoral artery and a three-way stopcock was attached to allow sampling of arterial blood and monitoring of arterial pressure (Figure 3). Blood clotting was prevented by flushing catheters with heparinized saline (4 units/ml). A single lumen 5 French catheter[d] with a thermistor[e] embedded in the tip[f] (Figure 4) was placed in the aorta via the external carotid artery.[25] Positioning was determined by fluoroscopy.[g]

Surgical Implantation and Preparation

Three days prior to study, each animal was implanted with the catheters and thermistor probe previously described. No premedication

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[a]Medical Grade Silastic Tubing, Dow Corning Corporation, Midland, Michigan.

[b]Three-Way Stopcock, Pharmaseal, Incorporated, Toa Alta, Puerto Rico 00758.

[c]Polycath IV, Jelco Laboratories, Raritan, New Jersey 08869.

[d]Cournand Single Lumen Catheter, U.S. Catheter and Instrument Company, P.O. Box 787, Glen Falls, New York 12801.

[e]Veco 32A7, Victory Engineering Corporation, Victory Road, Springfield, New Jersey 07081.

[f]Thermistor probe constructed by Mr. Frank Catina and Dr. Kenneth Holmes of Department of Physiology, Michigan State University, East Lansing, Michigan 48823.

[g]Model HRT, General Electric Company, Medical Systems Division, Detroit, Michigan 48219.

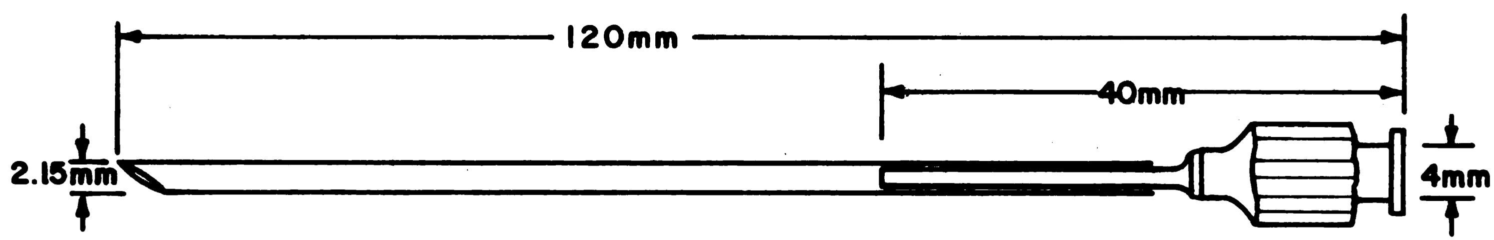

Figure 1. Silastic catheter with attached 15 gauge blunted needle for adaptation to a three-way stopcock.

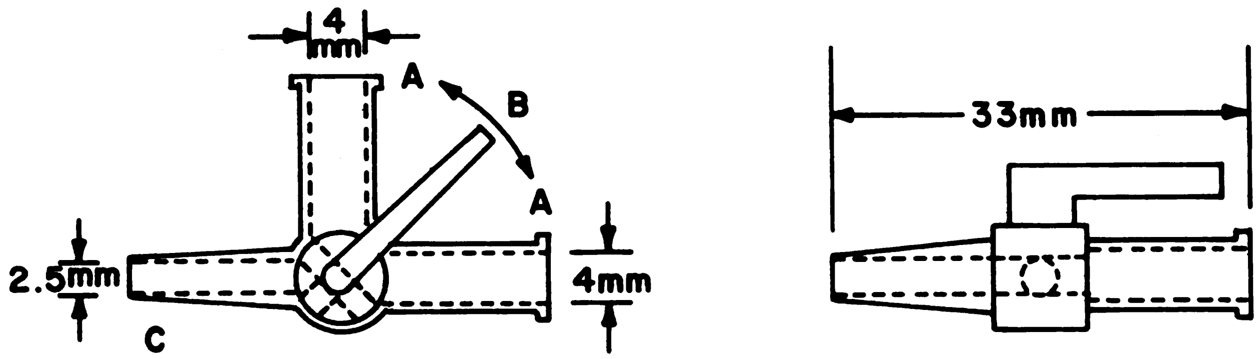

Figure 2. Three-way stopcock used for control of blood flow in arterial and venous catheters showing the method and direction of flow control.

A. Adapter allowing attachment of standard syringe and intravenous tubing adapters.
B. Handle allowing control of direction of flow through the stopcock.
C. Adapter allowing attachment of standard catheter adapters.

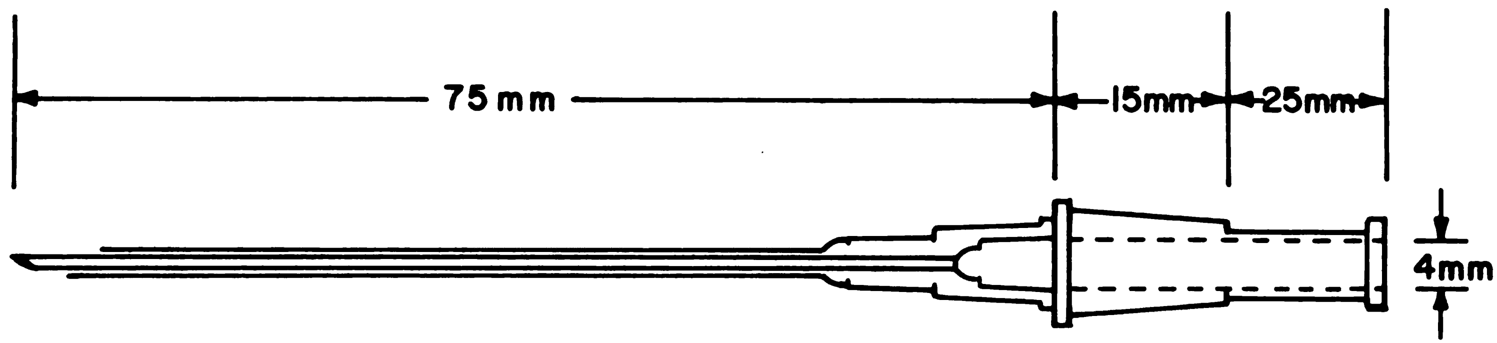

Figure 3. Polyethylene catheter used in the femoral artery showing placement of the catheter around a 21 gauge needle.

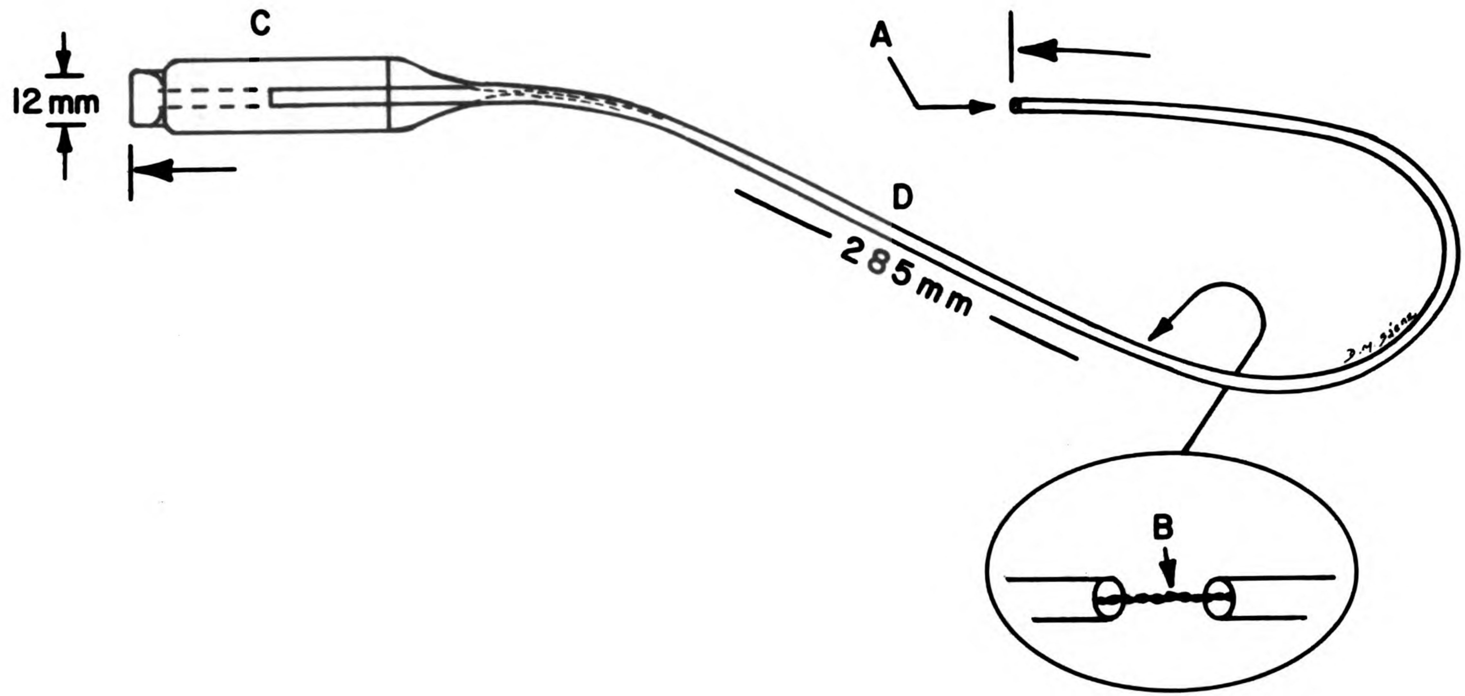

Figure 4. Diagram of thermistor probe placed in the descending aorta via the carotid artery.

A. Thermistor bead
B. Wires connecting thermistor bead and electrical adapter
C. Electrical adapter for connection to Wheatstone bridge
D. Five French catheter

was administered, and induction of anesthesia was accomplished by mask[a] with 4% halothane[b] in oxygen (5 l/min).[c] Tracheal intubation was accomplished, and anesthesia was maintained with 1.5-1.75% halothane with a total oxygen flow of 3 l/min via a Norman mask elbow.[d] The neck and the medial aspect of a rear leg were surgically prepared using a #40 surgical clipper blade[e] and iodine soap.[f] An iodine spray[g] was applied after the soap was removed with cotton wipes. The femoral artery was isolated through a medial 3-4 cm incision and tied off distally with 000 surgical silk.[h] The polyethylene catheter was placed and secured with three 000 silk ligatures. Skin was closed around the catheter with a single row of interrupted horizontal mattress sutures. Through a ventral incision in the neck, the jugular vein and carotid artery catheters were introduced, placed and secured in a similar manner. The placement of the aortic thermistor probe was aided by the infusion of a local anesthetic[i] around the carotid artery

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[a]Small Animal Facemask, Harris Colorific Company, Medical Division, Cleveland, Ohio 44102.

[b]Fluothane, Ayerst Laboratories, New York, New York 10017.

[c]Dupaco Dental Unit, Arcadia, California 91006.

[d]Norman Mask Elbow, Dupaco, Incorporated, San Marcos, California 92069.

[e]Oster Animal Electric Clipper Model A-2, Milwaukee, Wisconsin 53201.

[f]Betadine Solution, Purdue Frederick Company, Yonkers, New York 10701.

[g]Betadine Solution, Purdue Frederick Company, Yonkers, New York 10701.

[h]Nonabsorbable Surgical Sutures, Cardiovascular K-883-H, Somerville, New Jersey 08876.

[i]Lidocaine Hydrochloride Injection 2%, Wolins Pharmacal Corporation, Melville, New York 11746.

to decrease arterial constriction as the probe was advanced. Furacin powder[a] to prevent local infection and bandages to protect the implants were applied.

Equipment

An eight channel photographic recorder[b] was used during each study to visualize cardiovascular variables via an oscilloscope and to preserve a written record of the collected data (Figure 5). Cardiac output curves were obtained using the arterial thermistor probe connected to a pressure preamplifier via a Wheatstone bridge. Thermal dilution technique was used.[39] The thermistor was also connected to an electronic thermometer[c] through the Wheatstone bridge allowing monitoring of body temperature. Lead II electrocardiogram was constantly recorded. Arterial and venous pressure transducers[d] connected to preamplifiers were used for pressure recordings. Electronic averagers were used to obtain mean arterial and venous pressures. Heart rate was read from an electronic counter of arterial pulses. A pH electrode and a blood gas analyzer allowed determination of arterial PO_2, PCO_2, and pH. Base deficit was determined by the use of a nomogram.[37] A

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[a]Furacin Powder, Norwich Pharmacal Company, Norwich, New York 13815.

[b]Model DR-8, Electronics for Medicine, White Plains, New York 10601.

[c]Model 41TF, Yellow Springs Instrument Company, Yellow Springs, Ohio 45387.

[d]Model P23Db, Statham Transducers, Incorporated, Hato Rey, Puerto Rico 00919.

[e]Model 72EMD - RUPVEJ, Radiometer Copenhagen, Copenhagen, Denmark.

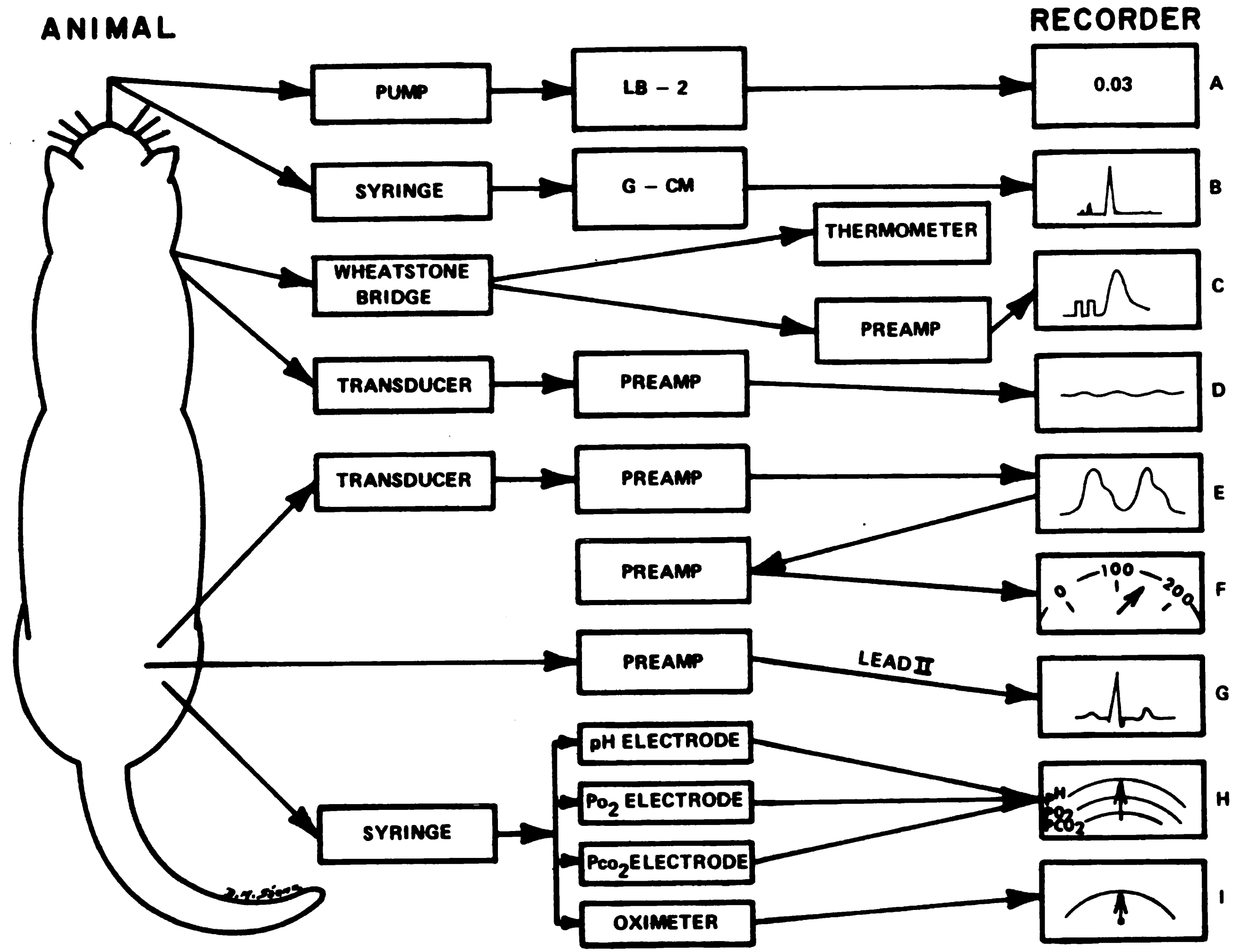

Figure 5. Diagram of equipment arrangement.

A. End-expired CO_2
B. End-expired halothane
C. Cardiac output
D. Mean venous pressure
E. Pulsatile arterial pressure
F. Heart rate
G. Lead II electrocardiogram
H. Meter for pH, P_aO_2 and P_aCO_2
I. Scale for O_2 saturation

colorimetric method[a] for determination of oxygen saturation of hemoglobin was utilized.

The same anesthetic machine[b] was used to deliver halothane and oxygen to all three anesthetic systems studied. A bubble type of vaporizer[c] was used for halothane vaporization. An Ayre's T-piece system[d] (Figure 6), a pediatric circle CO_2 absorption system[e] (Figure 7) and an adult circle CO_2 absorption system[f] (Figure 8) were used. The pediatric system contained a volume of 150 ml in the breathing hoses, 8 ml in the Y-piece, 250 ml in the soda lime canister, and 1000 ml in the rebreathing bag. Valves were made of lightweight plastic and were of the dome type. The Ayre's T-piece system contained volumes of 9 ml in the T-piece itself, 57 ml in the corrugated expiratory tube and 1000 ml in the rebreathing bag. There were no valves in the system. The adult system had volumes of 1174 ml in the breathing hoses, 19 ml in the Y-piece, 2000 ml in the soda lime canister and 2000 ml in the rebreathing bag. Dome type plastic valves were present. The total fresh gas flows used were 500 ml/min, 3 l/min and 500 ml/min for the pediatric, Ayre's and adult systems, respectively. The

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[a]Micro-oximeter, American Optical Company, Buffalo, New York 14201.

[b]Rotameter Model, The Foregger Company, 55 West 42nd Street, New York, New York 10036.

[c]Copper Kettle, The Foregger Company, 55 West 42nd Street, New York, New York 10036.

[d]Bissonette Ayre's T-piece (15 mm i.d.), Fraser Sweatman, Lancaster, New York 14086.

[e]Ohio Infant Circle, Ohio Chemical and Surgical Equipment, Madison, Wisconsin 53701.

[f]The Foregger Company, 55 West 42nd Street, New York, New York 10036.

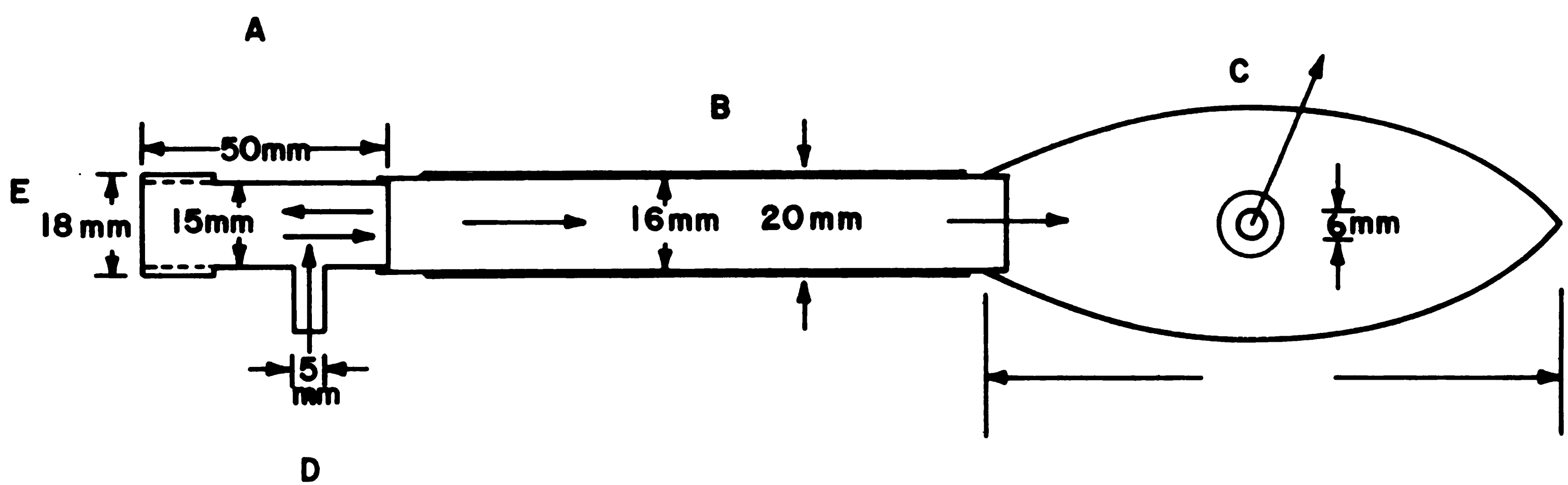

Figure 6. Ayre's T-piece system with dimensions and directions of gas flow.
A. Ayre's T-piece
B. Corrugated tubing
C. Reservoir bag with expiratory vent
D. Fresh gas inlet
E. To patient

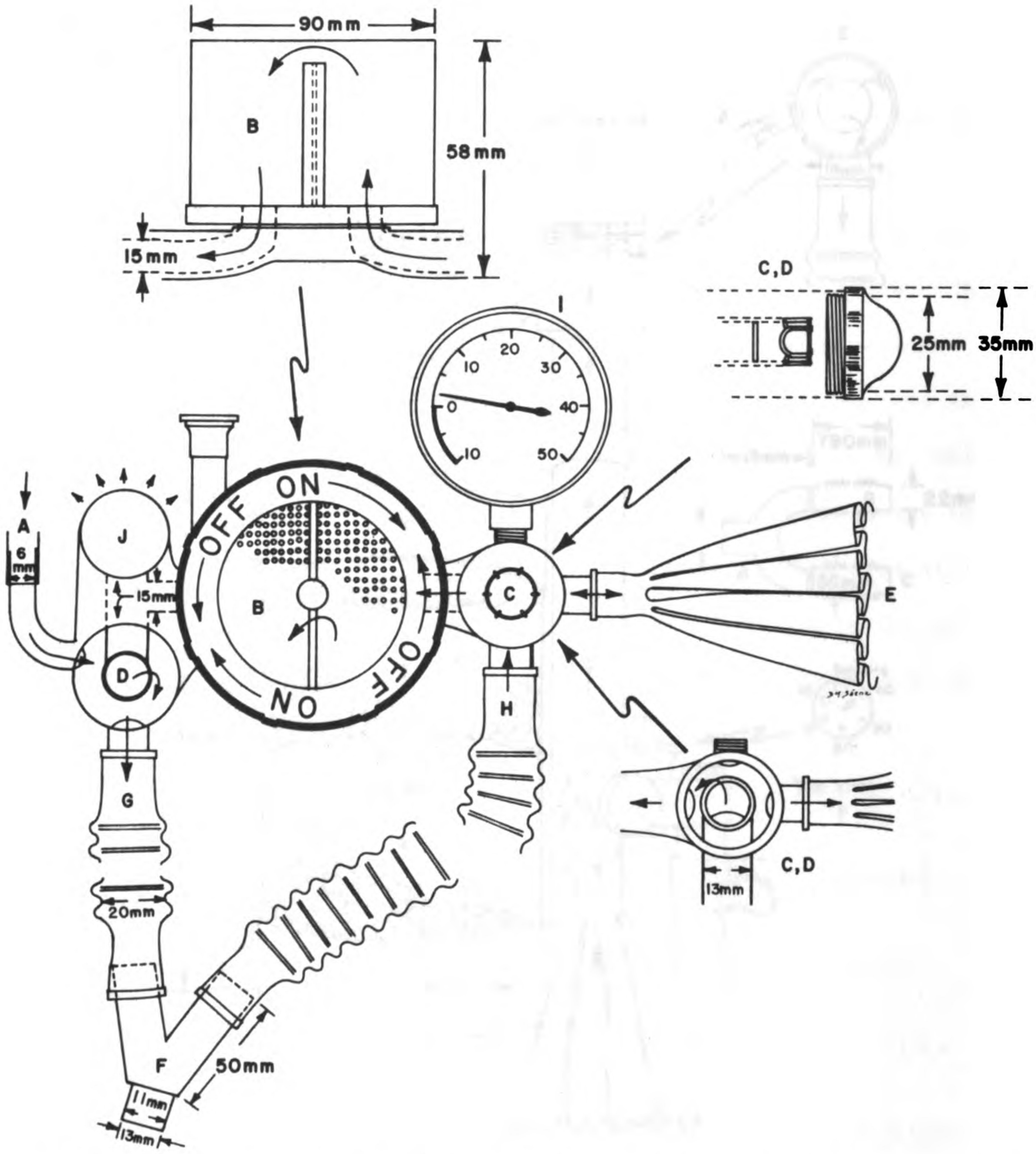

Figure 7. Pediatric circle CO_2 absorption system with dimensions and directions of gas flow.

A.	**Fresh gas inlet**	**F.**	**Y-piece**
B.	**Soda lime canister**	**G.**	**Inspiratory breathing hose**
C.	**Expiratory valve**	**H.**	**Expiratory breathing hose**
D.	**Inspiratory valve**	**I.**	**Pressure gauge**
E.	**Reservoir bag**	**J.**	**Overflow valve**

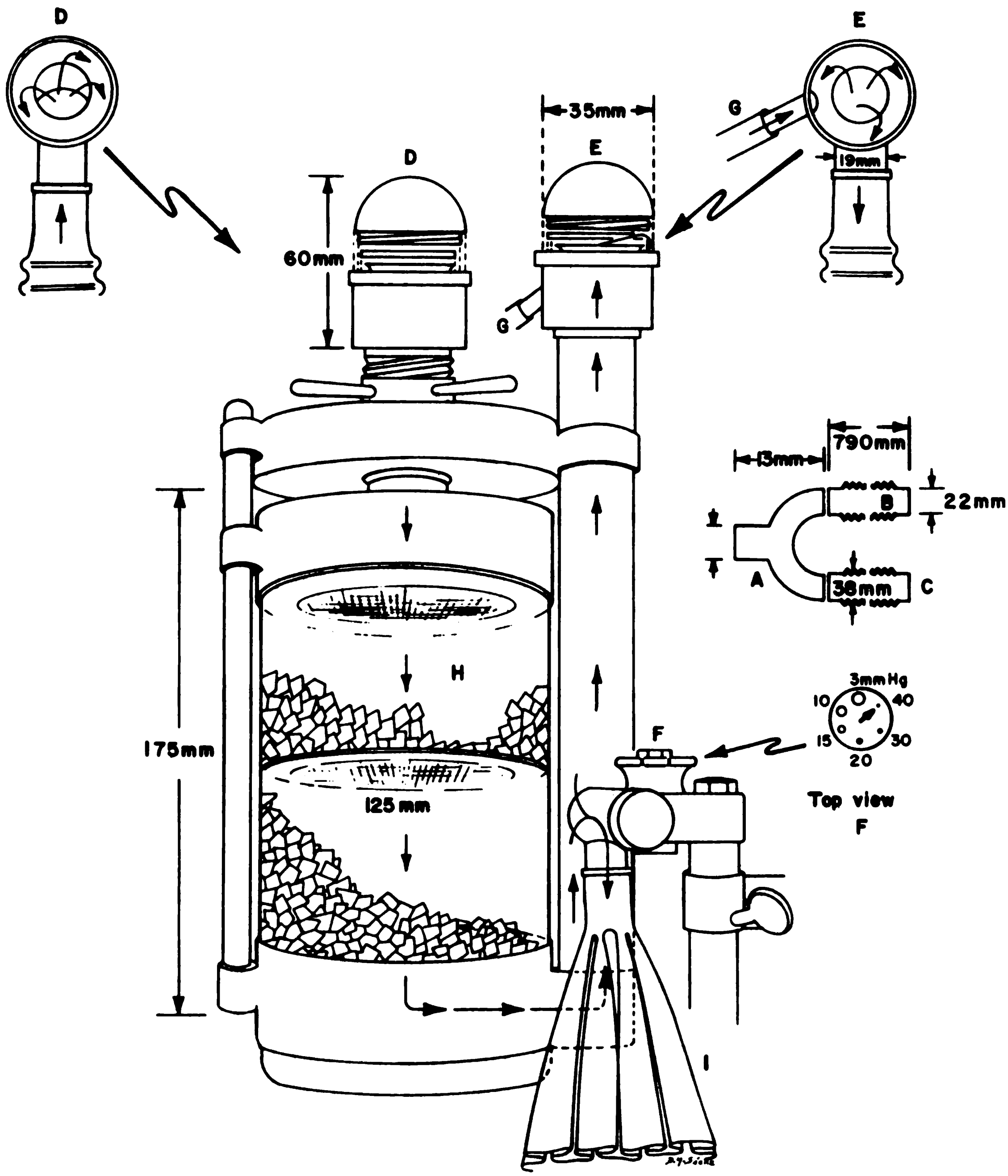

Figure 8. Adult circle CO_2 absorption system with dimensions and directions of gas flow.

A. Y-piece
B. Inspiratory breathing hose
C. Expiratory breathing hose
D. Expiratory valve
E. Inspiratory valve
F. Overflow valve
G. Fresh gas inlet
H. Soda lime canister
I. Reservoir bag

vaporizer flow was adjusted periodically to achieve an end-expiratory concentration of 1.4%. Body temperature of each cat as measured via the aortic thermistor was maintained above 36 C by use of a warm water circulating blanket.[a]

A carbon dioxide analyzer[b] was used to determine CO_2 concentration at the end of expiration. Samples were taken through a 5 French polypropylene tube[c] with the sampling port located at the distal end of the endotracheal tube[d] (Figure 9) which was secured in place. The cuffed endotracheal tube (Figure 9) was placed by use of a laryngoscope[e] and sterile lubricant[f] to prevent tracheal irritation, and the cuff was inflated to prevent inspiration of room air around the tube. Ten milliliter glass syringes[g] with three-way stopcocks were used to collect halothane samples from the tip of the endotracheal tube at the end of expiration via the polypropylene tube and from the outlet of the vaporizer via a 20 gauge hypodermic needle. A gas chromatograph

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[a]Model K-13, Gorman-Rupp Industries Company, Bellville, Ohio 44813.

[b]Medical Gas Analyzer LB-2, Beckman Instruments, Fullerton, California 92634.

[c]Polypropylene Catheter #5, Sherwood Medical Industries, Incorporated, St. Louis, Missouri 63101.

[d]Vinyl Endotracheal Tube #24987 (4 mm i.d.), Dupaco, Incorporated, Arcadia, California 91006.

[e]Foregger Folding Scope with a Miller #1 Blade, The Foregger Company, Incorporated, Roslyn Heights, Long Island, New York 11101.

[f]KY Sterile Lubricating Jelly, Johnson and Johnson, New Brunswick, New Jersey 08903.

[g]B-D Multifit Syringe, Quarry Company, Ann Arbor, Michigan 48106.

[h]Gaschromatograph GC-M, 115 Frankfurter Ringer, Munich, Germany.

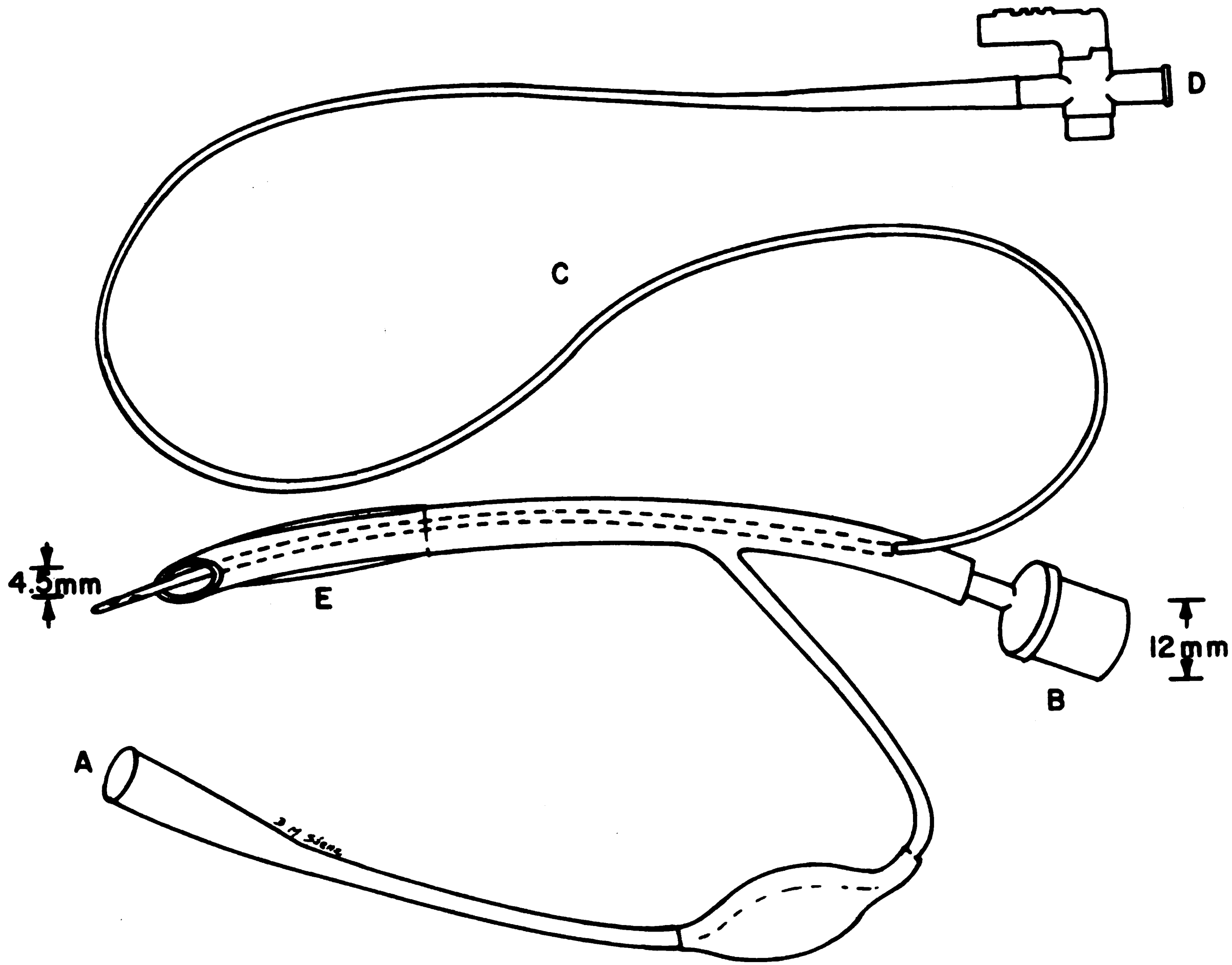

Figure 9. Endotracheal tube showing sampling catheter and stopcock for taking end-expired gas samples.

A. Endotracheal tube cuff inflation port
B. Adapter
C. Sampling tube (length= 48 cm)
D. Three-way stopcock
E. Cuff

was used to determine halothane concentration of gas samples. A 15 in x 1/8 in stainless steel screened 60/80 mesh silica gel column was used. Column and detector temperatures of 165 C and 200 C, respectively, were maintained. Gases used were H_2 at 50 psi flowing 60 ml/min, air at 50 psi flowing 300 ml/min and N_2 at 60 psi flowing 100 ml/min.

Procedure for Recording Data

On the day of the study, the cat was weighed and brought to the laboratory where the neck bandage was removed and a jugular vein blood sample taken. After determination of heart rate, respiratory rate and end-expiratory CO_2 concentration, a control cardiac output was recorded usually without excitement of the animal. The bandage over the femoral catheter was removed and an arterial blood sample was taken. This procedure usually caused some discomfort to the animal due to manipulation of the catheter. Pressure transducers were placed at the level of the heart, and control values for arterial and venous pressures were recorded. The animal was then anesthetized with 4% halothane by mask with an oxygen flow of 5 l/min. Intubation and inflation of the endotracheal tube cuff were accomplished, and anesthetic concentration was adjusted to achieve an end-expiratory concentration approaching 1.4% halothane. Measurements were taken every 15 minutes for 135 minutes yielding ten recording periods including the control measurement.

Data Measurement

Cardiac output was determined using a thermal dilution technique employing room temperature saline (0.9%).[39] Measurements were made at the control time and at 15 minute intervals during anesthesia. Room temperature saline was injected through the jugular catheter, and the total volume injected minus the dead space of the catheter and stopcock was 1.0 ml. In each animal, the tip of the catheter was positioned near the right atrium. The injectate then passed through the pulmonary circulation to the descending aorta where the change in temperature was detected by the thermistor. The change in temperature was recorded as a curve due to the fall in temperature of blood passing the thermistor. Prior to each injection and recording, a standard deflection equal to a change of 0.1 C was produced by a 3 ohm resistor built into the Wheatstone bridge. Before each injection, animal temperature, injectate temperature and injectate volume were recorded. The area of the curve was determined by constructing a triangle under the curve[39] and direct measurement using a planimeter.[a] The area was determined three times, and an average value was used for the curve area. Paper speed was verified for each output curve by use of time lines. Calculation of cardiac output was by the following modified Stewart-Hamilton formula:[39]

$$CO = \frac{V_i\ (T_b - T_i)\ (R)\ (F)}{A}$$

where: CO = cardiac output in ml/min

V_i = volume of the injectate in ml

T_b = temperature of the blood in degrees Centigrade

T_i = temperature of the injectate in degrees Centigrade

R = standard deflection due to 3 ohm resistor given in cm/C

F = paper speed in cm/min

A = area under the curve in cm^2

[a]K and E Compensating Polar Planimeter, Keuffel and Esser Company, New York, New York 10017.

From cardiac output determinations, cardiac index, stroke volume and total peripheral vascular resistance were calculated. The following formulas were utilized in these calculations:[28,55]

$$CI = \frac{CO}{BSA}$$

$$SV = \frac{CO}{HR} \times 1000$$

$$TPVR = \frac{MAP - MVP}{CO}$$

where: CI = cardiac index

CO = cardiac output in l/min

BSA = body surface area in m^2

HR = heart rate in beats/min

SV = stroke volume in ml

TPVR = total peripheral vascular resistance in peripheral vascular resistance units (PRU)

MAP = mean arterial pressure in mm Hg

MVP = mean venous pressure in mm Hg

Body surface area was determined using a nomogram corresponding to the values given by the formula, $m^2 = 0.087\ kg^{2/3}$, using body weight as a standard multiplied by a coefficient of prediction[6] for cats. Body weights were determined in pounds using a standard infant scale[a] prior to each study, and conversion to kilograms was done mathematically.

Arterial and venous pressures were read directly from a scale on the oscilloscope. Arterial pressure was read from a scale with a range of 200 mm Hg, and venous pressure was measured on a range of

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[a]Pediatric Scale Model 322 (36 lb capacity), Health-o-Meter, Continental Company, Quarry Company, Ann Arbor, Michigan 48106.

10 mm Hg. Arterial pressure values were recorded for systolic, diastolic and mean values, but only mean venous pressure was recorded. The transducers were filled with physiological saline and calibrated before each study. Preamplifiers were balanced for reactive and restrictive components of the gauge impedence. Balancing was done at both high and low ranges, and calibration was completed following setting of the baseline. The arterial monitoring system was calibrated with an input equal to 50 mm Hg, and the venous system was calibrated using 5 mm Hg. Built-in gain and amplitude adjustments allowed proper calibration.

Carbon dioxide sampling was done only at 15 minute intervals to prevent removal of excessive amounts of gas from the lungs because of the small lung volume of these animals. Values for end-expiratory CO_2 concentrations were read direclty from the digital meter of the CO_2 analyzer. The analyzer baseline was set at a reading of 0.03% in room air, and calibration was completed by use of a known CO_2[a] concentration of 6.87% prepared by Scholander technique.[58] Calibration was usually repeated once during each study and more often if the baseline was noted to change.

Halothane concentrations were determined from samples (5 ml) aspirated with glass syringes.[57] End-expiratory samples were taken over five to eight respirations due to the rapid respiratory rates of the cats. Sampling was done at the tip of the endotracheal tube near the bifurcation of the bronchi. To measure the concentration of halothane delivered to each system, samples (5 ml) were taken through a 20 gauge needle from the hose coming directly from the mixing chamber of the anesthetic machine. All halothane samples were subjected to

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[a] CO_2 - 6.87%. Prepared by the Department of Physiology, Michigan State University, East Lansing, Michigan 48823.

gas chromatography for analysis.[57] Calibration involved the injection of a known concentration of halothane (0.80%)[57] and determining the deflection of a pen on a recorder. Unknown halothane samples were compared and calculated as proportional values because the chromatograph used was linear over the range of halothane concentrations in this study. The following formula was used to determine the unknown concentration (x) in per cent:

$$x = \left[\frac{\text{Halothane Standard (\%)}}{\text{Standard Deflection (mm)}}\right]\left[\text{Sample Deflection (mm)}\right]$$

Arterial blood gas, pH and oxygen saturation determinations were done on all samples including controls. Arterial pH determinations were made using a pH electrode calibrated prior to each study using standard buffers with pH's equal to 6.840 and 7.381. The P_aCO_2 electrode was calibrated with two standards, 11.90% CO_2 and 2.95% CO_2. The O_2 electrode was calibrated with 20.95% O_2. Recalibration was done only if there was reason to suspect deviation from true values. Oxygen saturations were determined with a micro-oximeter which was balanced and standardized with a standard saturation of 83%. All arterial gas and pH measurements were done using heparinized samples of blood (1 ml) from the femoral artery. All measurements were made within 2 minutes.

Comparison of Systems

Animals were grouped into three groups of six animals each to form the pediatric circle group (Group I), the Ayre's T-piece group (Group II) and the adult circle group (Group III). All groups were handled in the same manner except that a total oxygen flow of 3 l/min was used for Group I while an oxygen flow of 500 ml/min was used for

Groups II and III. Therefore, differences among groups were assumed to be due to differences in the systems.

Data Analysis

Analysis of data was done through the facilities of the Computer Laboratory of Michigan State University. Comparisons of body weights, hematocrit, white blood cell count, total serum protein, serum hemoglobin, BUN and SGPT values were made using a single classification analysis of variance.[61] Control values for all respiratory and cardiovascular variables were compared with the same type of analysis to determine variability of controls for each group. Comparison of groups was by Tukey's w-procedure.[61] Analysis of variance was used to supply means and standard deviations and to test for variation among groups at each data collection point in time, i.e., 15 minutes after anesthesia induction. Regression analysis with time was done, and analysis of variance was performed to determine variation between regression coefficients among groups. Finally, an analysis of variance[61] at 15, 75 and 135 minutes was performed allowing partitioning of the total sum of squares into components due to end-tidal halothane concentration, variation in controls and variation due to anesthetic systems. A level of significance of 0.05 was considered statistically significant for this study.

RESULTS

General Considerations

Twenty-six cats were used in this study. Of eight cats not included in the data, two were used to perfect technique, two were dropped due to excessive white blood cell counts on the study day, two had nonfunctional femoral artery catheters and two died following surgical procedures of implantation. Cause of death was hemorrhage due to loosening of the three-way stopcock from the femoral artery catheter. After completion of each study, the catheters and thermistor probe were removed from each cat. Each animal was then recovered and survived. Recovery times were not recorded.

Mean values and standard deviations for WBC count, hemoglobin, hematocrit, total protein, BUN, SGPT and arterial pH for study groups are shown in Table 1. By analysis of variance, these values were not statistically different among groups at a significance level of $P<0.05$. Mean body weights are also shown in Table 1, and these values were not statistically different.

After surgical implantation, each cat was used for only one anesthetic system evaluation. Although data were recorded ten times during a study at 15 minute intervals to provide 180 data points for each experiment, Tables 2 through 7 list data at 30 minute intervals due to small magnitude of value variability during the study.

TABLE 1

BLOOD EVALUATIONS

	GROUP I	GROUP II	GROUP III
SGPT (SF units)	21±10	34±26	15±3
BUN (mg/100 ml)	23±8	27±10	24±1
WBC (cells/mm^3)	14,483±5,158	11,638±7.453	13,000±3,050
PCV (%)	32±6	35±6	30±4
Hb (gm/100 ml)	11±2	12±2	10±3
Protein (gm/100 ml)	5.8±.8	5.7±.9	5.8±1.0
pH	7.38±0.09	7.40±.06	7.39±0.03

Mean and standard deviation values recorded from jugular vein blood samples except pH, which was determined using a femoral artery sample.

During each study, body temperature and end-tidal halothane concentration were controlled. Body temperature (Tables 3, 5 and 7) measured by the aortic thermistor probe was maintained above 36 C for all animals. Temperatures for Groups I, II, and III had decreased 5%, 4.5% and 5.2%, respectively, from control measurements at the end of study. End-tidal halothane concentration was maintained at approximately 1.4% by varying inspired halothane concentration. At each data point, halothane concentration among the three groups was not statistically different ($P<0.05$) for either end-tidal or inspired halothane concentrations (Figure 10).

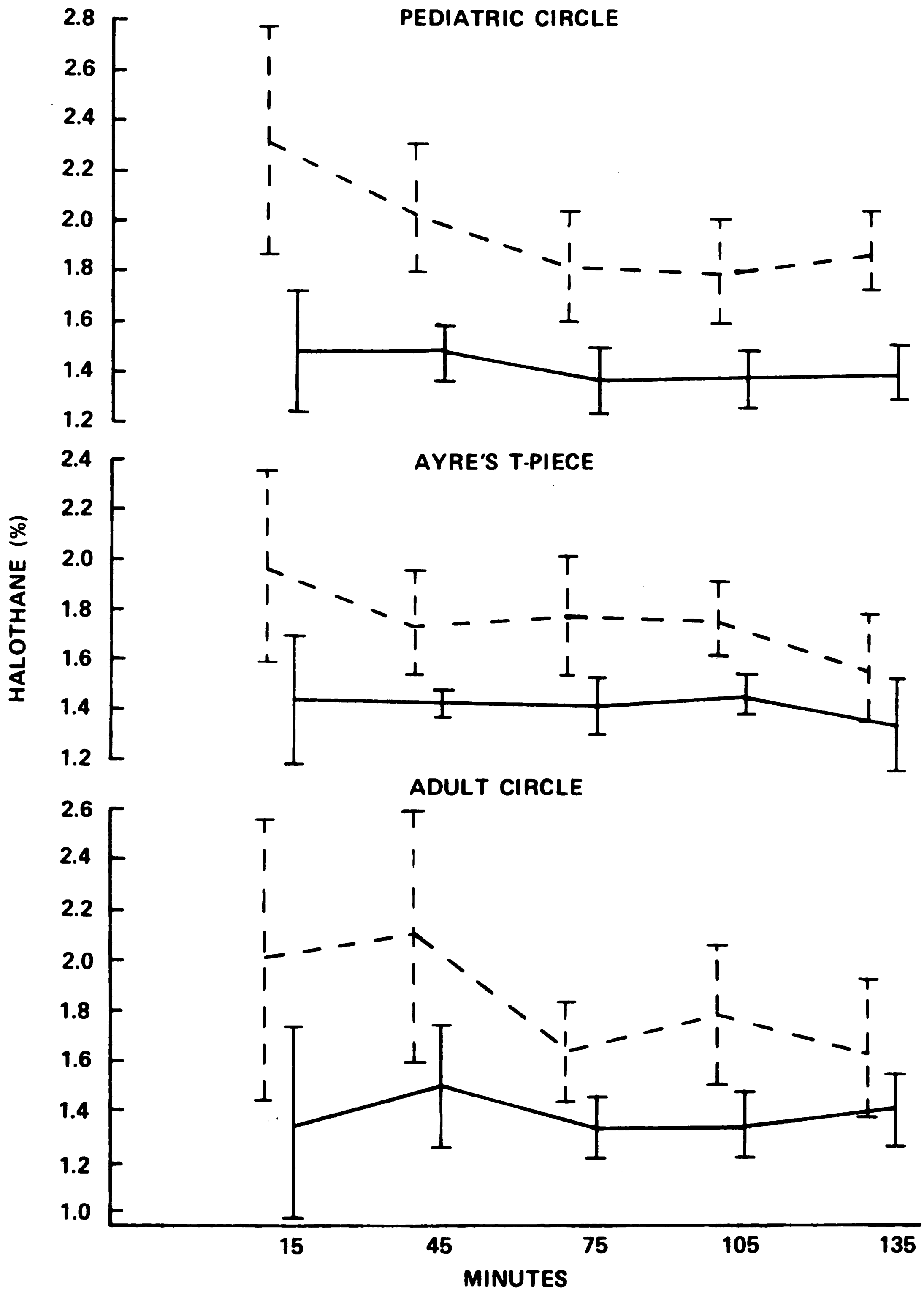

Figure 10. Halothane concentrations from six cats are plotted at 30 minute intervals for each of three groups,
------------- = inspired halothane
———— = end-expired* halothane
Values are means ± standard deviations
*** Respiration was spontaneous.**

Pediatric Circle Reabsorption System (Group I)

Mean and standard deviation values for cardiopulmonary variables from six 3.3 $\pm$ .7 kg cats maintained with the pediatric circle system are given in Tables 2 and 3. Mean cardiac output (CO) was decreased from control 30-35% throughout the period of anesthesia. Mean cardiac index (CI) was similarly affected. Following induction of anesthesia, magnitude of change of CI and CO with time was small. Mean heart rate (HR) decreased with time and was 16% lower than control at the last data point. Mean stroke volume (SV) for the group was decreased in a variable manner from approximately 11-24%. SV increased when HR decreased to maintain the relatively constant CO. Total peripheral vascular resistance (TPR) was depressed 6-20% from control, and this depression was greater with time. Mean venous pressure (MVP) was generally higher than control until the last data point. However, the highest value was seen immediately after induction, and then decreased gradually. Arterial pressure was decreased from control at all points during study. Generally mean, systolic and diastolic pressure were lowered by about the same percentage. Mean arterial pressure (MAP) was lowered 30-42% at any data point. Arterial pH was lower than the control value throughout study. The decrease from control was greater with time reaching a maximum decrease of 1.5% at 135 minutes. Mean base deficit (BD) increased to 52% above control. Mean P_aO_2 increased as anesthesia began and remained 350-400% above control. Mean arterial O_2 saturation was increased up to 2.3%. Mean P_aCO_2 was 15-27% above control. Mean values for end-expired CO_2 were 25-41% above control. P_aCO_2 and end-expired CO_2 values are plotted in Figure 11. Mean respiratory rate (RPM) was lower than control at all points, but tended to return toward control. Immediately

TABLE 2

CARDIOVASCULAR VARIABLES OF GROUP I (PEDIATRIC CIRCLE)

TIME (min)	CONTROL	15	45	75	105	135
TEMP (C)	40.0 ± .6	39.4 ± .4	38.9 ± .5	38.5 ± .7	38.2 ± .9	38.0 ± 1.0
CO (l/min)	.586 ± .118	.405 ± .107	.380 ± .071	.395 ± .059	.402 ± .060	.394 ± .054
CI	2.75 ± .84	1.91 ± .68	1.77 ± .43	1.84 ± .36	1.86 ± .33	1.83 ± .37
HR (beats/min)	182 ± 30	167 ± 26	156 ± 18	155 ± 18	151 ± 23	153 ± 22
SV (ml)	3.27 ± .77	2.49 ± .82	2.49 ± .69	2.58 ± .49	2.89 ± .66	2.64 ± .62
TPR (PRU)	18.1 ± 4.9	17.0 ± 4.1	16.3 ± 2.4	15.4 ± 2.3	14.5 ± 2.7	15.4 ± 2.4
MVP (mm Hg)	3 ± 3	6 ± 2	4 ± 2	4 ± 3	3 ± 3	3 ± 3
MAP (mm Hg)	106 ± 14	73 ± 14	65 ± 10	64 ± 9	61 ± 11	63 ± 6

Mean and standard deviation values recorded for six cats for each variable at 15 minutes before induction of halothane anesthesia (control) and at 30 minute intervals during maintenance of anesthesia.

TEMP = temperature of aortic blood; CO = cardiac output; CI = cardiac index; HR = heart rate; SV = stroke volume; TPR = total peripheral resistance; MVP = venous pressure; MAP = arterial pressure.

TABLE 3

RESPIRATORY VARIABLES OF GROUP I (PEDIATRIC CIRCLE)

TIME (min)	CONTROL	15	45	75	105	135
HAL_{EE} (%)	...	1.51 $\pm$ .11	1.51 $\pm$ .11	1.41 $\pm$ .13	1.42 $\pm$ .11	1.45 $\pm$ .11
HAL_{IS} (%)	...	2.28 $\pm$ .52	2.07 $\pm$ .24	1.85 $\pm$ .21	1.83 $\pm$ .21	1.90 $\pm$ .16
RPM (breaths/min)	45 $\pm$ 8	34 $\pm$ 5	40 $\pm$ 6	43 $\pm$ 6	43 $\pm$ 7	45 $\pm$ 9
P_eCO_2 (mm Hg)	24 $\pm$ 6	33 $\pm$ 6	32 $\pm$ 8	31 $\pm$ 8	30 $\pm$ 6	30 $\pm$ 7
P_aCO_2 (mm Hg)	26 $\pm$ 3	32 $\pm$ 7	32 $\pm$ 7	29 $\pm$ 5	30 $\pm$ 6	31 $\pm$ 6
pH	7.38 $\pm$ .09	7.27 $\pm$ .11	7.28 $\pm$ .07	7.31 $\pm$ .08	7.30 $\pm$ .07	7.27 $\pm$ .08
P_aO_2	102 $\pm$ 11	468 $\pm$ 62	493 $\pm$ 25	485 $\pm$ 50	515 $\pm$ 58	528 $\pm$ 133
O_2SAT (%)	93 $\pm$ 2	96 $\pm$ 2	95 $\pm$ 1	95 $\pm$ 1	95 $\pm$ 2	94 $\pm$ 2
BD	-8 $\pm$ 4	-12 $\pm$ 5	-11 $\pm$ 3	-10 $\pm$ 4	-11 $\pm$ 4	-12 $\pm$ 3

Mean and standard deviation values recorded for six cats for each variable at 15 minutes before induction of halothane anesthesia (control) and at 30 minute intervals during maintenance of anesthesia.

HAL_{EE} = end-expired halothane concentration; HAL_{IS} = impaired halothane concentration; RPM = respirations/min; P_eCO_2 = end-expired CO_2; P_aCO_2 = partial pressure of CO_2 in arterial blood; PO_2 = partial pressure of oxygen in arterial blood; O_2SAT = oxygen saturation of arterial blood; BD = base deficit.

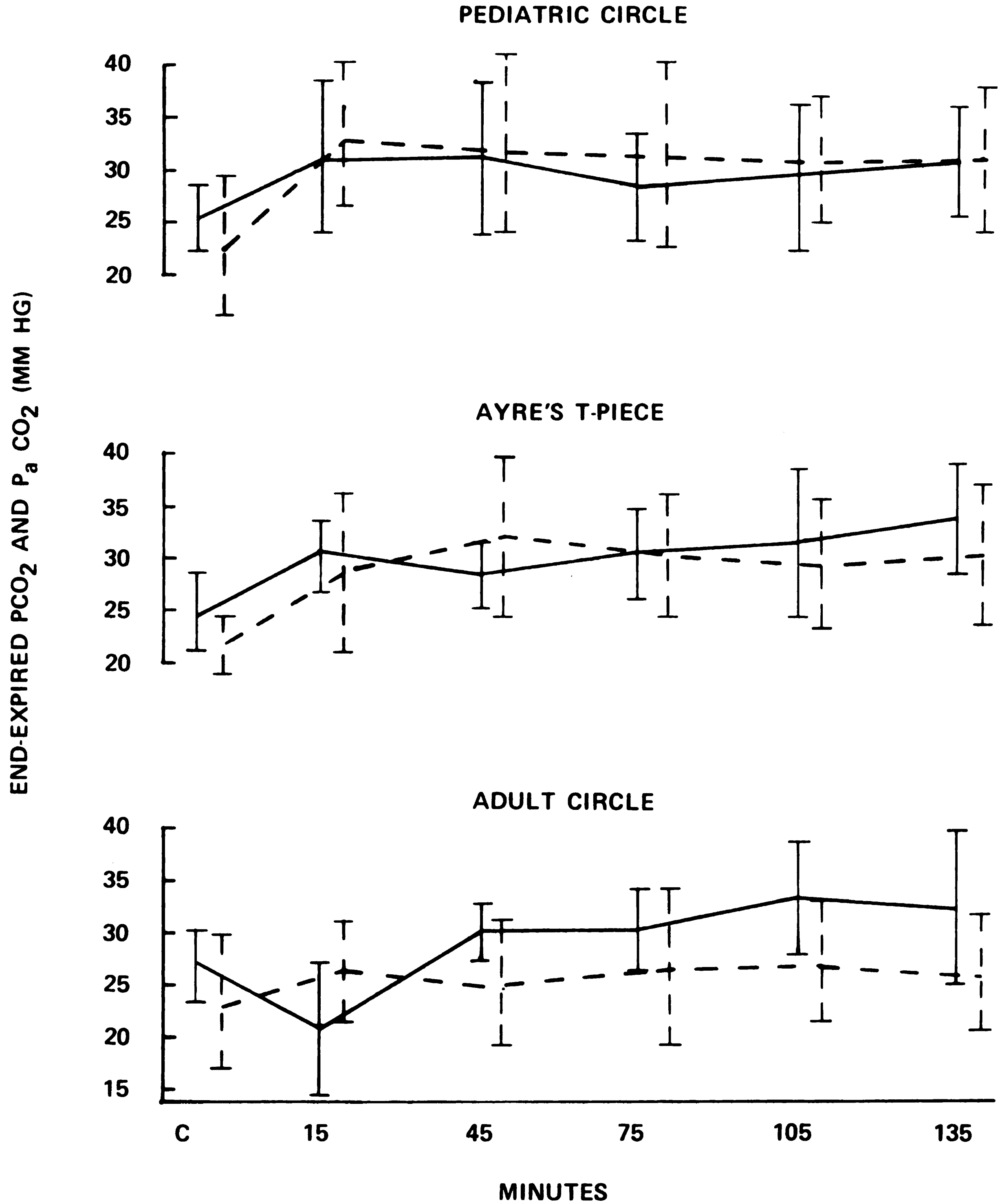

Figure 11. Pressures of CO_2 from six cats are plotted at 30 minute intervals for each of three groups,

----------- = end-expired* CO_2

——— = P_a CO_2

Values are means $\pm$ standard deviations. Control measurements were taken 15 minutes prior to anesthesia induction.

* Respiration was spontaneous.

after induction the rate was approximately 25% below control and at 135 min, only 1.5% below control.

Ayre's T-piece System (Group II)

Six cats with a mean body weight of 3.6 ± .7 kg were maintained during halothane anesthesia with an Ayre's T-piece system. Mean and standard deviation values are listed for cardiopulmonary variables in Tables 4 and 5. Mean CO was decreased approximately 37-40% below control at all data points. CI was similarly decreased. SV and HR were both decreased 22-27% below control throughout anesthesia maintenance. TPR was increased 19% at 15 minutes post-induction, but at other points it was 2-5% below control. MVP was 92% above control at the first data point and decreased steadily until the last data point where the mean decrease was 30%. Mean, systolic and diastolic arterial pressures were depressed approximately the same at each data point. MAP was 24-39% below control during maintenance of anesthesia. Arterial pH was lower than control throughout the study reaching a maximum decrease of 1.8% at the last data point. Mean BD was consistently increased above control and reached a maximum increase of 68% at 135 minutes. Mean P_aO_2 was 350-450% above control at all data points. Mean values for arterial O_2 saturation of hemoglobin increased to 2.3% above control, but were variable. Mean P_aCO_2 was increased 18-37% above control at all data points, and the change tended to increase with time. Mean values for end-expired CO_2 were 26-43% above control during study. These CO_2 values are plotted together in Figure 11. Mean respiratory rate was decreased 28-36% from control.

TABLE 4

CARDIOVASCULAR VARIABLES OF GROUP II (AYRE'S T-PIECE)

TIME (min)	CONTROL	15	45	75	105	135
TEMP (C)	39.6 ± .5	39.2 ± .6	38.7 ± .6	38.3 ± .7	38.0 ± .8	37.8 ± .9
CO (1/min)	.666 ± .142	.413 ± .083	.416 ± .076	.404 ± .103	.412 ± .106	.412 ± .087
CI	2.96 ± 1.02	1.77 ± .32	1.81 ± .46	1.76 ±.57	1.80 ± .60	1.79 ± .49
HR (beats/min)	215 ± 24	167 ± 27	159 ± 22	160 ± 23	158 ± 29	160 ± 30
SV (ml)	3.41 ± .53	2.51 ± .50	2.63 ± .39	2.50 ± .41	2.65 ± .66	2.60 ± .40
TPR (PRU)	15.3 ± 3.8	18.2 ± 6.7	14.9 ± 3.1	15.5 ± 4.9	14.5 ± 5.0	14.8 ± 4.4
MVP (mean mm Hg)	2 ± 3	4 ± 2	3 ± 2	2 ± 1	2 ± 1	2 ± 2
MAP (mean mm Hg)	100 ± 10	77 ± 21	63 ± 12	62 ± 13	61 ± 14	63 ± 14

Mean and standard deviation values for six cats for each variable recorded 15 minutes before induction of halothane anesthesia (control) and at 30 minute intervals during maintenance of anesthesia.

TEMP = temperature of aortic blood; CO = cardiac output; CI = cardiac index; HR = heart rate; SV = stroke volume; TPR = total peripheral resistance; MVP = venous pressure; MAP = arterial pressure.

TABLE 5

RESPIRATORY VARIABLES OF GROUP II (AYRE'S T-PIECE)

TIME (min)	CONTROL	15	45	75	105	135
HAL_{EE} (%)	...	1.45 ± .26	1.45 ± .06	1.43 ± .10	1.47 ± .07	1.38 ± .14
HAL_{IS} (%)	...	1.97 ± .37	1.74 ± .21	1.79 ± .22	1.75 ± .13	1.59 ± .20
RPM (breaths/min)	71 ± 21	49 ± 16	45 ± 14	50 ± 14	51 ± 16	48 ± 16
P_eCO_2 (mm Hg)	23 ± 2	30 ± 7	33 ± 7	31 ± 6	29 ± 6	30 ± 6
P_aCO_2 (mm Hg)	25 ± 4	31 ±3	29 ± 3	31 ± 4	32 ± 7	34 ± 5
pH	7.40 ± .06	7.32 ± .09	7.31 ± .06	7.30 ± .04	7.29 ± .06	7.27 ± .07
P_aO_2 (mm Hg)	96 ± 11	481 ± 94	434 ± 213	490 ± 176	527 ± 129	527 ± 139
O_2SAT (%)	94 ± 2	96 ± 2	94 ± 2	95 ± 2	95 ± 2	94 ± 2
BD	-7 ± 5	-10 ± 5	-10 ± 3	-10 ± 2	-11 ± 3	-11 ± 4

Mean and standard deviation values for six cats for each variable recorded 15 minutes before induction of halothane anesthesia (control) and at 30 minute intervals during maintenance of anesthesia.

HAL_{EE} = end-expired halothane concentration; HAL_{IS} = inspired halothane concentration; RPM = respirations/min; P_eCO_2 = end-expired CO_2; P_aCO_2 = partial pressure of CO_2 in arterial blood; P_aO_2 = partial pressure of oxygen in arterial blood; O_2SAT = oxygen saturation of arterial blood; BD = base deficit.

Adult Circle Reabsorption System (Group III)

Six cats, 3.2 $\pm$ .6 kg body weight, were used for data collection for the adult circle group. Mean and standard deviation values for cardiopulmonary variables are presented in Tables 6 and 7. Mean CO was 29-34% below control. CI followed a similar pattern. Mean HR for the group was decreased 15-20% during study time, and mean SV was lowered 13-19%. Mean TPR remained 7-26% below control throughout anesthesia. MVP was consistently above control, but values decreased with time. MVP was 84% above control at the end of the study. Mean, systolic and diastolic arterial pressures were consistently depressed in approximately the same magnitude at each data point. MAP was 33-45% below control. Arterial pH was lower than control at all data points reaching a maximum decrease of approximately 2% at the end of study. BD consistently increased with time reaching a maximum of 85% above control at the last data point. Mean P_aO_2 was 390-430% above control at all points during anesthesia. Mean O_2 saturation was essentially unchanged throughout study. Mean P_aCO_2 was increased 14-23% above control during study. Mean end-expired CO_2 increased 10-18% during anesthesia. Both CO_2 values are plotted in Figure 11. Mean respiratory rate was variably increased or decreased reaching a maximum of 13% above control.

Comparison of Systems and Statistical Analysis Results

Statistical analysis of data was done for all variables measured for the pediatric circle, the Ayre's T-piece and the adult circle. For each variable, regression analysis with time showed significant differences ($P<0.05$) between the pediatric and adult circles for pH

TABLE 6

CARDIOVASCULAR VARIABLES OF GROUP III (ADULT CIRCLE)

TIME (min)	CONTROL	15	45	75	105	135
TEMP (C)	39.2 ± .6	38.7 ± 1.0	38.2 ± 1.0	37.6 ± 1.1	37.4 ± 1.2	37.2 ± 1.4
CO (l/min)	.544 ± .157	.365 ± .113	.365 ± .076	.384 ± .051	.375 ± .053	.360 ± .051
CI	2.65 ± 1.05	1.79 ± .75	1.77 ± .54	1.87 ± .51	1.82 ± .44	1.75 ± .46
HR (beats/min)	202 ± 30	169 ± 32	162 ± 37	170 ± 39	170 ± 44	164 ± 44
SV (ml)	2.72 ± .83	2.22 ± .68	2.35 ± .76	2.47 ± .69	2.34 ± .64	2.37 ± .80
TPR (PRU)	22.9 ± 10.5	21.2 ± 12.7	16.8 ± 5.9	18.2 ± 6.5	18.8 ± 6.8	18.6 ± 6.1
MVP (mean mm Hg)	1 ± 1	3 ± 2	4 ± 3	2 ± 2	2 ± 2	3 ± 2
MAP (mean mm Hg)	115 ± 18	77 ± 23	63 ± 17	71 ± 22	71 ± 27	67 ± 28

Mean and standard deviation values for six cats for each variable recorded 15 minutes before induction of halothane anesthesia (control) and at 30 minute intervals during maintenance of anesthesia.

TEMP = temperature of aortic blood; CO = cardiac output; CI = cardiac index; HR = heart rate; SV = stroke volume; TPR = total peripheral resistance; MVP = venous pressure; MAP = arterial pressure.

TABLE 7

RESPIRATORY VARIABLES OF GROUP III (ADULT CIRCLE)

TIME (min)	CONTROL	15	45	75	105	135
HAL_{EE}(%)	...	1.32 ± .37	1.56 ± .25	1.34 ± .10	1.36 ± .10	1.43 ± .14
HAL_{IS}(%)	...	2.02 ± .56	2.11 ± .56	1.66 ± .17	1.79 ± .25	1.86 ± .26
RPM (breaths/min)	52 ± 22	45 ± 15	56 ± 17	51 ± 16	54 ± 19	55 ± 10
P_eCO_2 (mm Hg)	24 ± 6	27 ± 4	26 ± 5	27 ± 7	28 ± 6	26 ± 5
P_aCO_2 (mm Hg)	27 ± 3	21 ± 6	30 ± 2	31 ± 4	33 ± 5	33 ± 7
pH	7.39 ± .03	7.33 ± .07	7.29 ± .05	7.28 ± .04	7.27 ± .08	7.25 ± .09
P_aO_2 (mm Hg)	104 ± 11	510 ± 96	523 ± 59	510 ± 81	547 ± 101	527 ± 133
O_2SAT (%)	95 ± 2	94 ± 2	94 ± 2	95 ± 3	95 ± 1	94 ± 1
BD	-7 ± 2	-9 ± 4	-11 ± 3	-12 ± 2	-12 ± 3	-13 ± 3

Mean and standard deviation values for six cats for each variable recorded 15 minutes before induction of halothane anesthesia (control) and at 30 minute intervals during maintenance of anesthesia.

HAL_{EE} = end-expired halothane concentration; HAL_{IS} = inspired halothane concentration; RPM = respirations/min; P_eCO_2 = end-expired CO_2; P_aCO_2 = partial pressure of CO_2 in arterial blood; P_aO_2 = partial pressure of oxygen in arterial blood; O_2SAT = oxygen saturation of arterial blood; BD = base deficit.

and base deficit. Figures 12 and 13 indicate the differences for these two variables showing generally opposite trends following induction. However, actual values for the groups were quite close as time progressed. No differences were noted for other variables.

Analysis of variance showed no statistical difference ($P<0.05$) among groups at any data point for any variable. Mean and standard deviation values are plotted in Figures 10 through 19 allowing comparisons of the groups for each variable.

Finally, analysis of variance partitioning the total sum of squares at every data point for variation due to halothane, controls and groups yielded a statistically significant difference only for O_2 saturation at 15 minutes due to groups. Oxygen saturation differences were clinically unimportant.

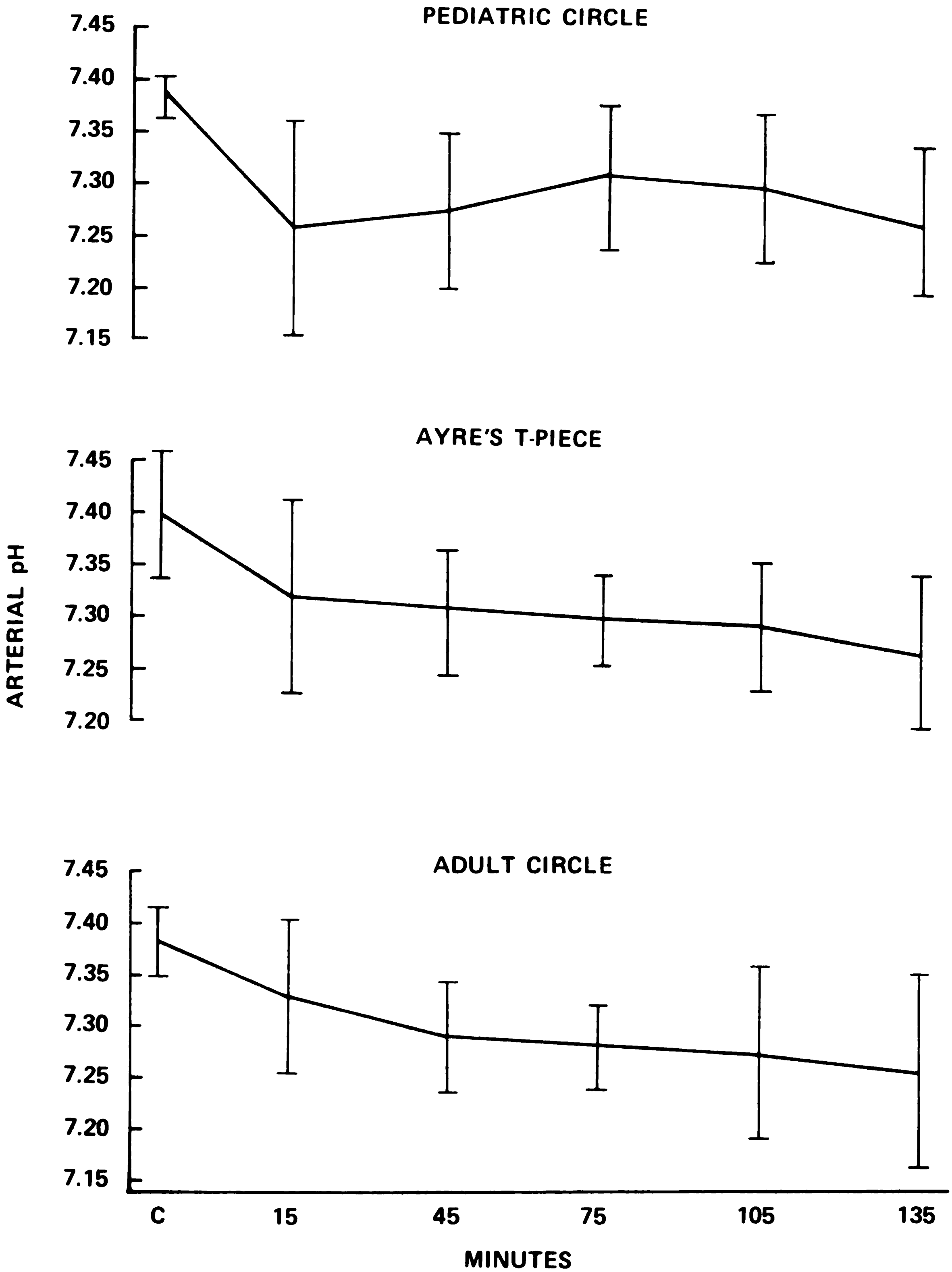

Figure 12. Arterial pH values are plotted at 30 minute intervals for three groups of six cats following induction of halothane anesthesia. Control (C) measurements were obtained 15 minutes prior to anesthesia induction. Values are means $\pm$ standard deviations.

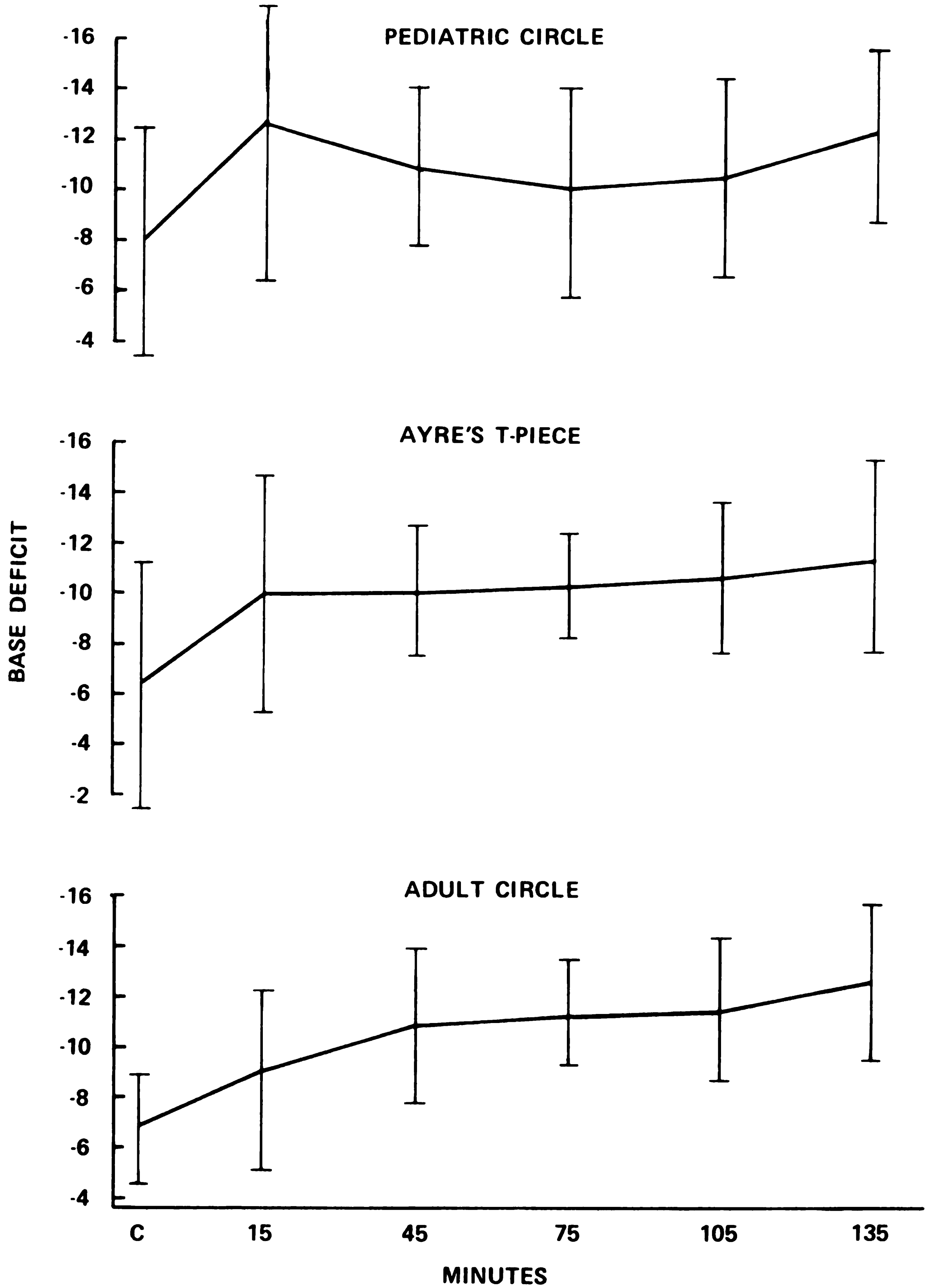

Figure 13. Base deficit values are plotted at 30 minute intervals for three groups of six cats following induction of halothane anesthesia. Control (c) measurements were obtained 15 minutes prior to anesthesia induction. Values are means ± standard deviations.

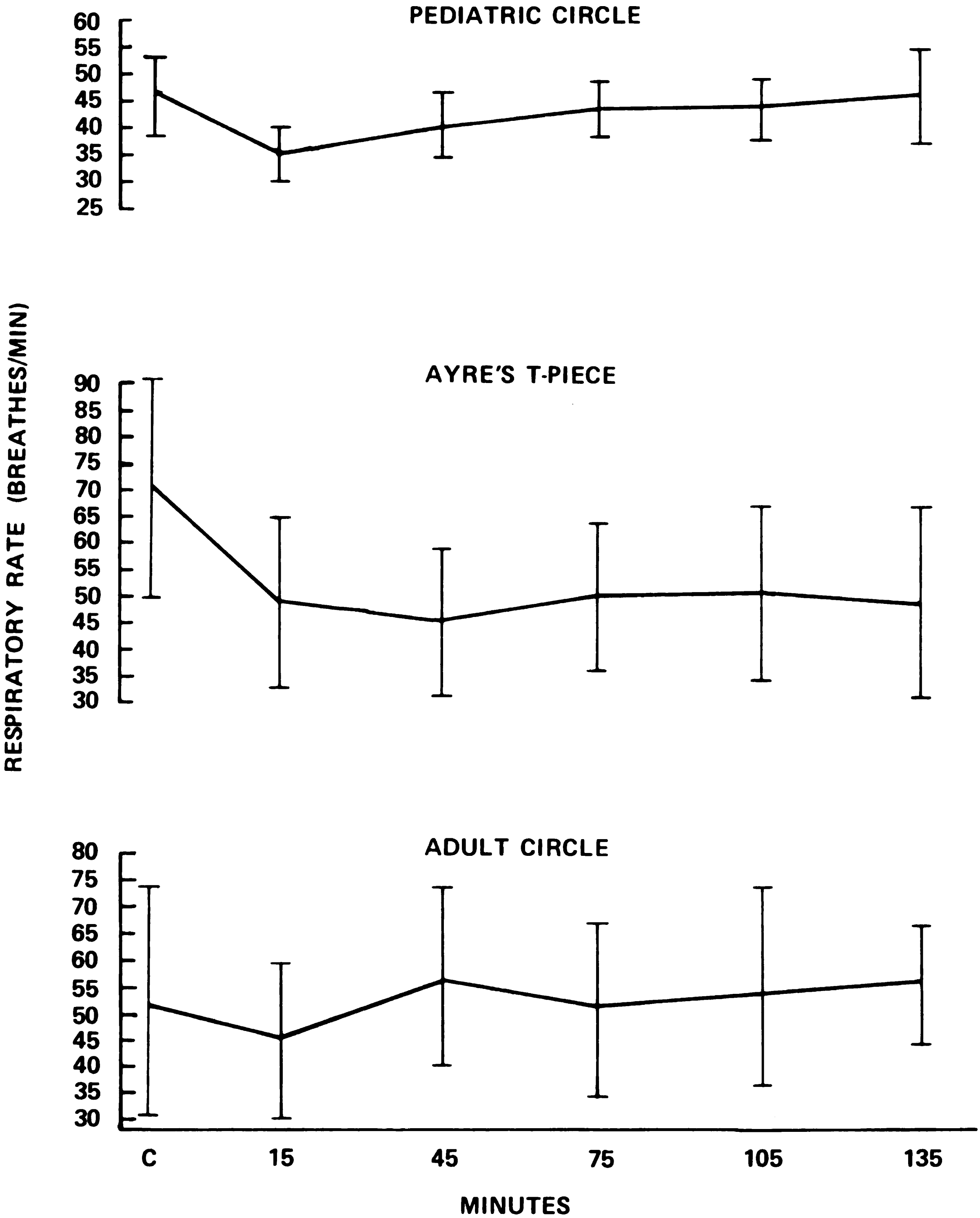

Figure 14. Respiratory rate values are plotted at 30 minute intervals for three groups of six cats following induction of halothane anesthesia. Control (C) measurements were obtained 15 minutes prior to anesthesia induction. Values are means ± standard deviations.

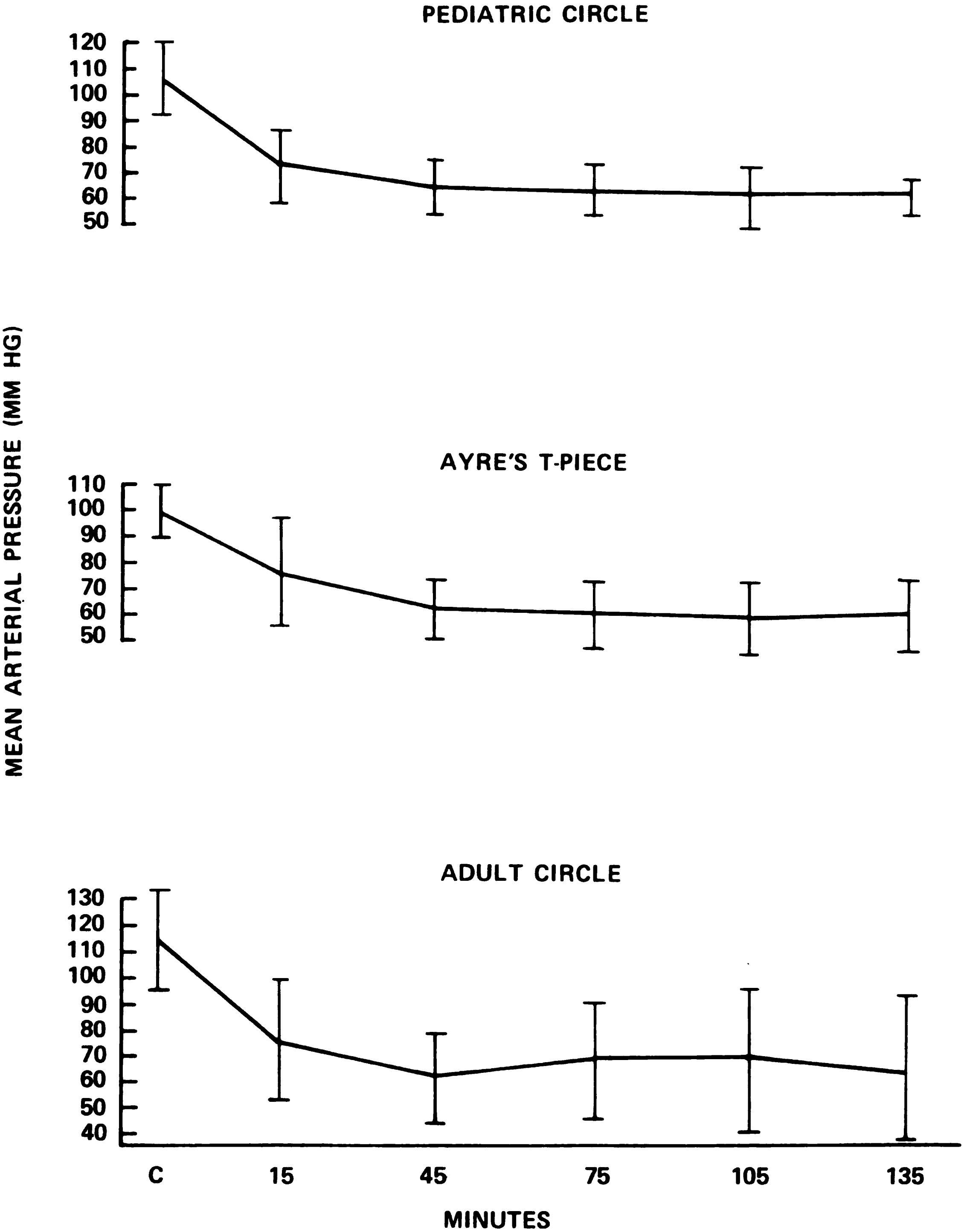

Figure 15. Mean arterial pressure values are plotted at 30 minute intervals for three groups of six cats following induction of halothane anesthesia. Control (C) measurements were obtained 15 minutes prior to anesthesia induction. Values are means $\pm$ standard deviations.

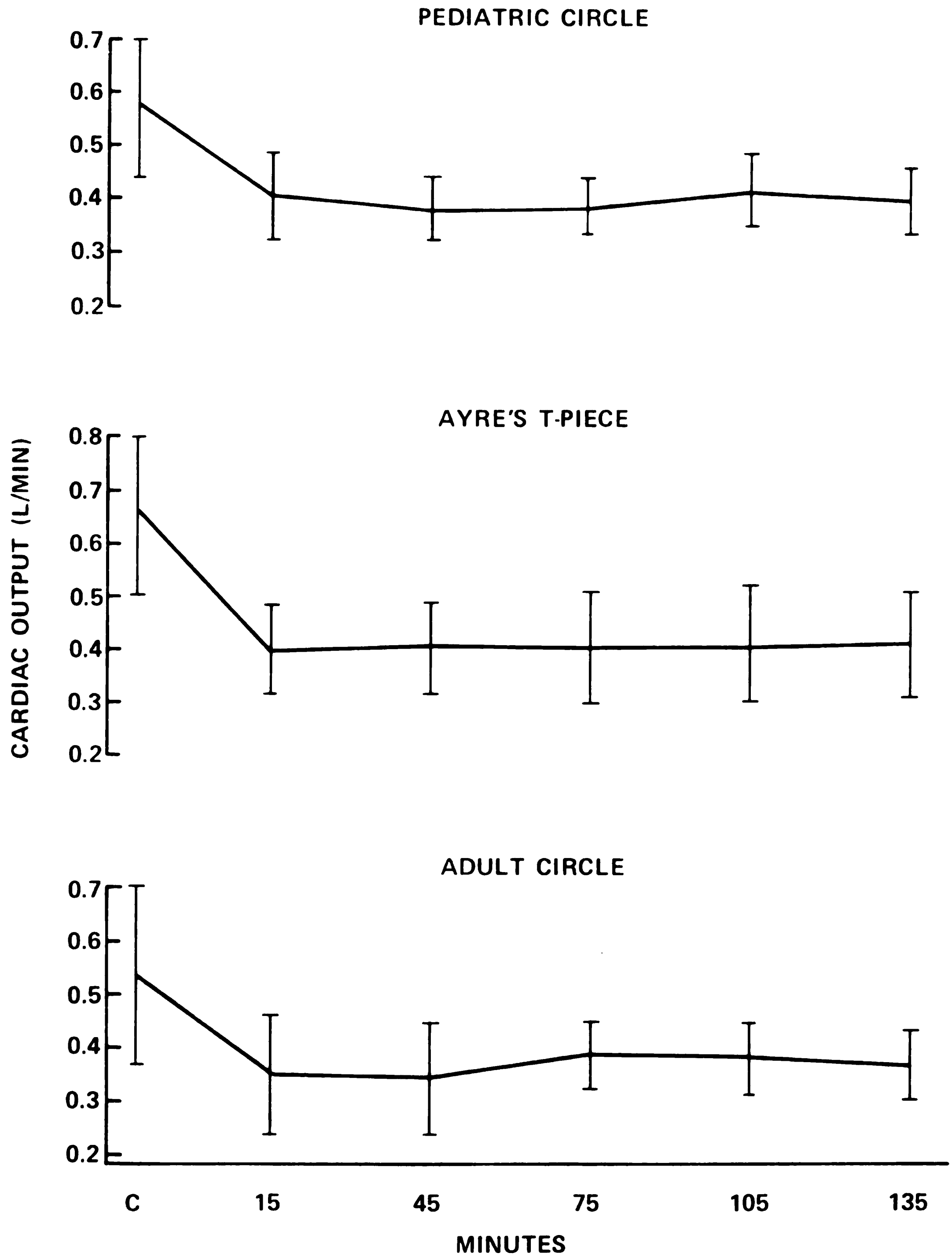

Figure 16. Cardiac output values are plotted at 30 minute intervals for three groups of six cats following induction of halothane anesthesia. Control (C) measurements were obtained 15 minutes prior to anesthesia induction. Values are means ± standard deviations.

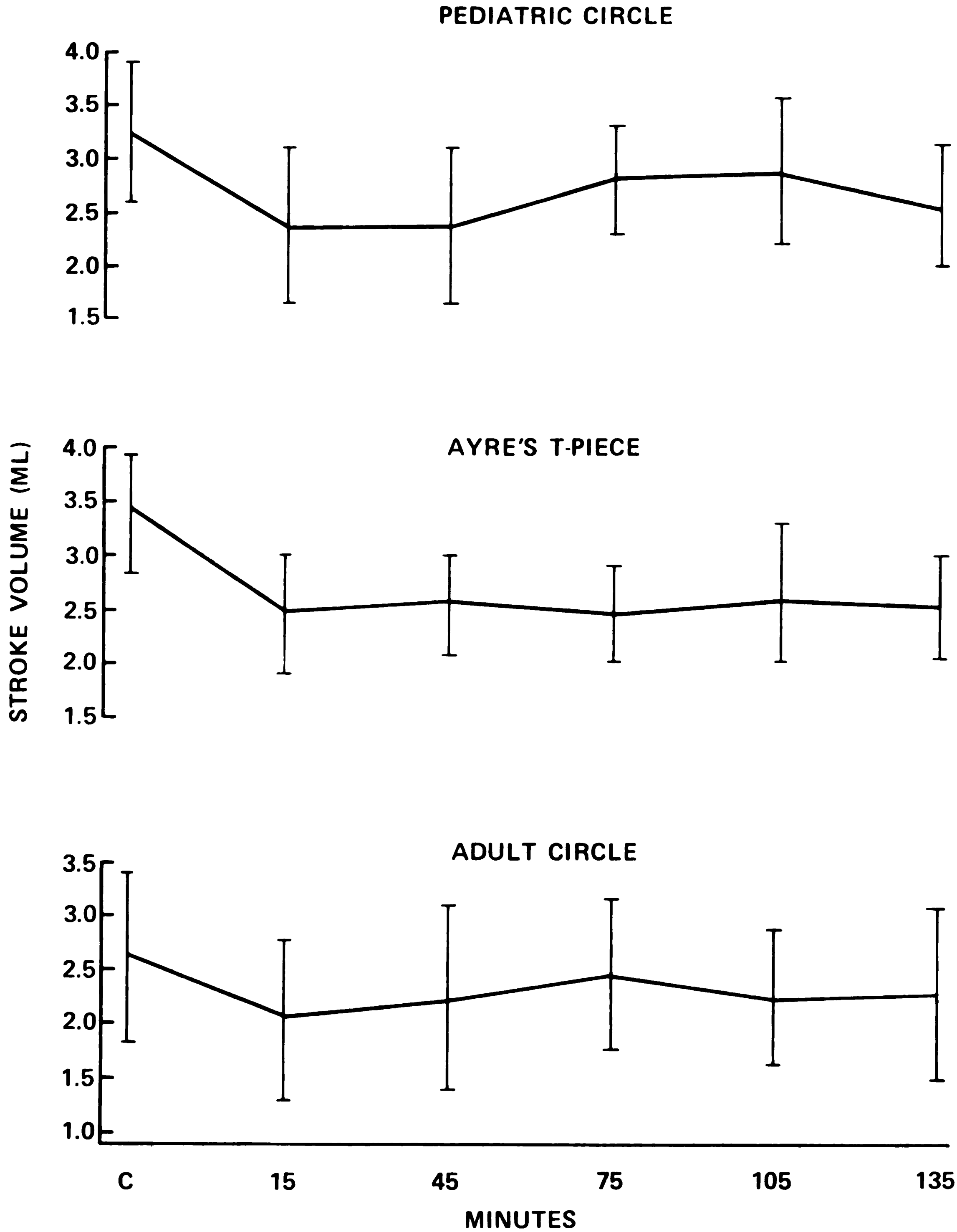

Figure 17. Stroke volume values are plotted at 30 minute intervals for three groups of six cats following induction of halothane anesthesia. Control (C) measurements were obtained 15 minutes prior to anesthesia induction. Values are means ± standard deviations.

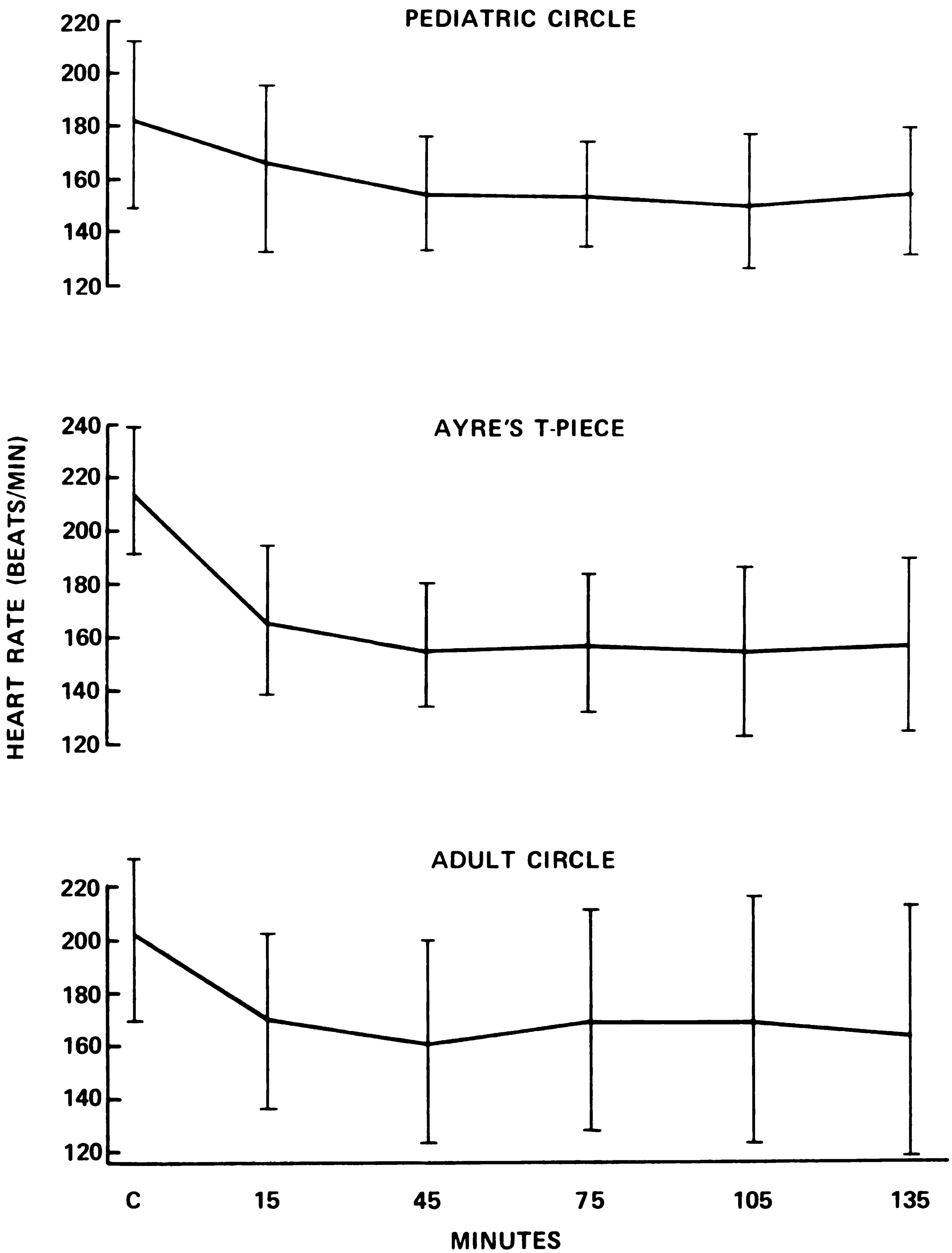

Figure 18. Heart rate values are plotted at 30 minute intervals for three groups of six cats following induction of halothane anesthesia. Control (C) measurements were obtained 15 minutes prior to anesthesia induction. Values are means $\pm$ standard deviations.

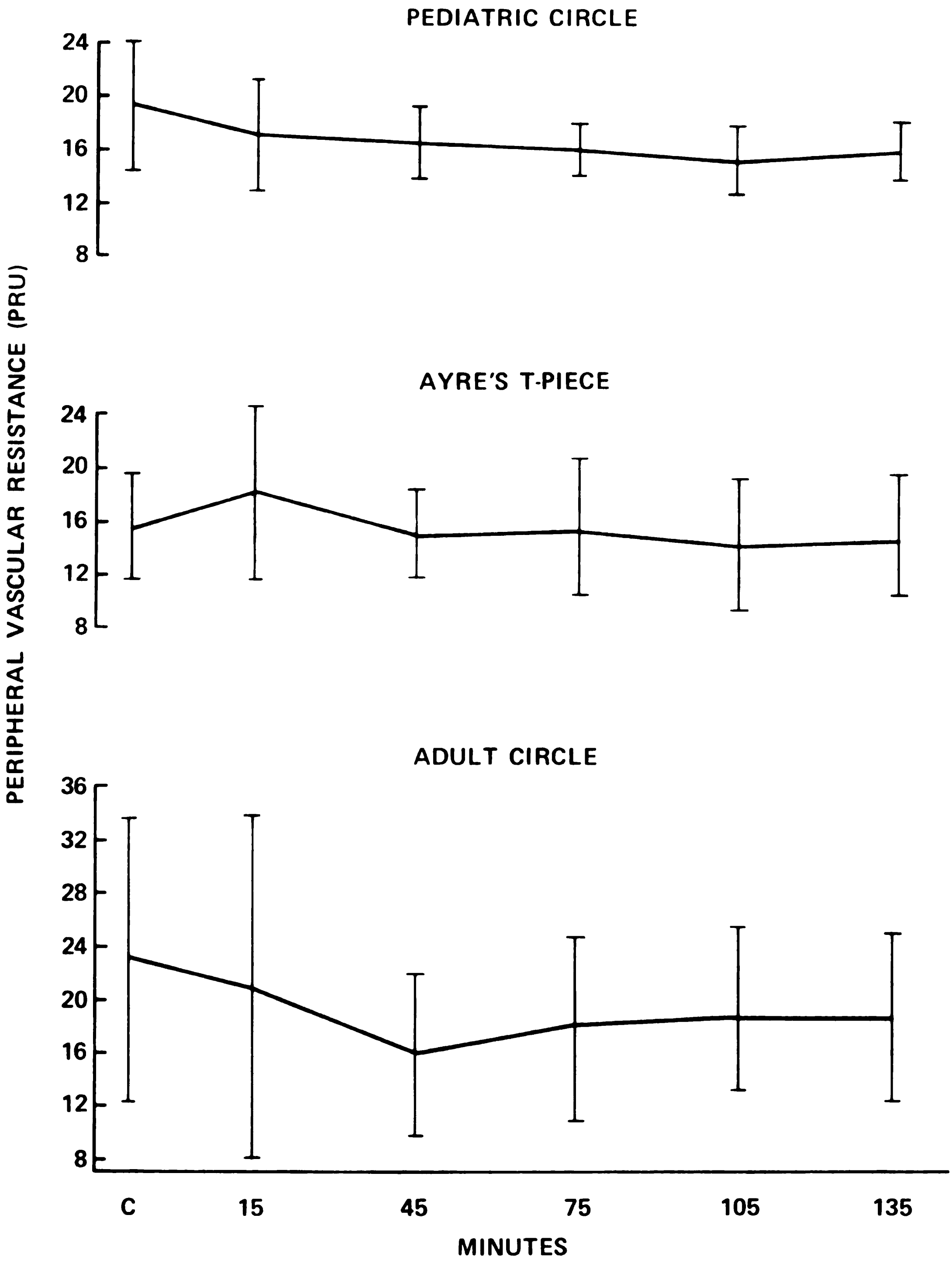

Figure 19. Total peripheral vascular resistance values are plotted at 30 minute intervals for three groups of six cats following induction of halothane anesthesia. Control (C) measurements were obtained 15 minutes prior to anesthesia induction. Values are means $\pm$ standard deviations.

DISCUSSION AND CONCLUSIONS

The main conclusion of this study was that normal, healthy cats could maintain relatively similar states of their cardiovascular and pulmonary systems with any of the three systems studied. Therefore, from these data, adult circle systems, pediatric circle systems and Ayre's T-piece systems may be equally recommended for maintenance of halothane anesthesia in spontaneously breathing normal cats. This study agreed with data of Graff *et al.*[27] which showed no significant differences in acid-base balance in babies alternated between an adult circle and a Y-piece during halothane anesthesia. Therefore, recommendations by other workers[3,4,34,62,63,65,66] are not supported by the findings of this study.

Although no clinically important physiological variations among systems were found in this study, these results cannot be applied totally to every species or every condition of patient health. Ver Steeg and Stevens[68] found that the T-piece and pediatric circle required less patient inspiratory effort than adult circle systems, a factor that might be of great importance in conditions of poor patient health.

Several factors may have influenced results obtained from this study. One influence was collection of control data. Animals varied in apprehension, and this affected some control data, particularly arterial blood gases. Also, collection of end-expired CO_2 samples from awake cats by placing the sampling catheter in the mouth was quite inaccurate. Dead space in the stopcock used for injection of saline during cardiac output determinations caused some change in temperature of the injectate. However, this was a relatively constant factor in each cat allowing valid output comparisons. Some error may have existed in area determination of cardiac output curves due to judgment in drawing triangular lines. A typical set of curves (Figure 20) indicates that curves were repeatable, and the cats were generally undisturbed by collection of control CO data. Rapid respiratory rates made sampling of end-expired gases less accurate, and therefore mixed inspired and end-expired samples were possible. Also, the placement of pressure transducers at the cardiac level by judgment could have induced error. Individual animal variability often caused large standard deviations from mean values. A need for larger numbers of experimental cats is indicated if, in fact, only small differences among systems exist. However, such small differences might not be clinically significant. Various errors in rounding off data must have been present.

Changes in variables that occurred following halothane anesthesia induction were related to the anesthetic. Cardiac output was generally decreased for all groups in a range of 30-40%. Although no reports of changes in CO in cats anesthetized with halothane alone were available, reports in man indicate a 31% decrease[59] in CO, while decreases in swine have been 50%.[55] Dobkin *et al.*[20] reported that CO in dogs was depressed 31% during 2% halothane anesthesia. After an extensive review of the literature, Sawyer[55] reported that halothane depressed CO by approximately 30%. Hence, CO changes in this study appear to be of a magnitude related to halothane anesthesia. Stroke volume was decreased 11-26% in cats. Generally, reports from the literature indicate about a 20% depression in SV.[55] In this study, heart rate was depressed 8-26%. Beaton[7] reported a 30% decrease in heart rate while using 1.5% halothane in cats previously anesthetized with chloralose. However,

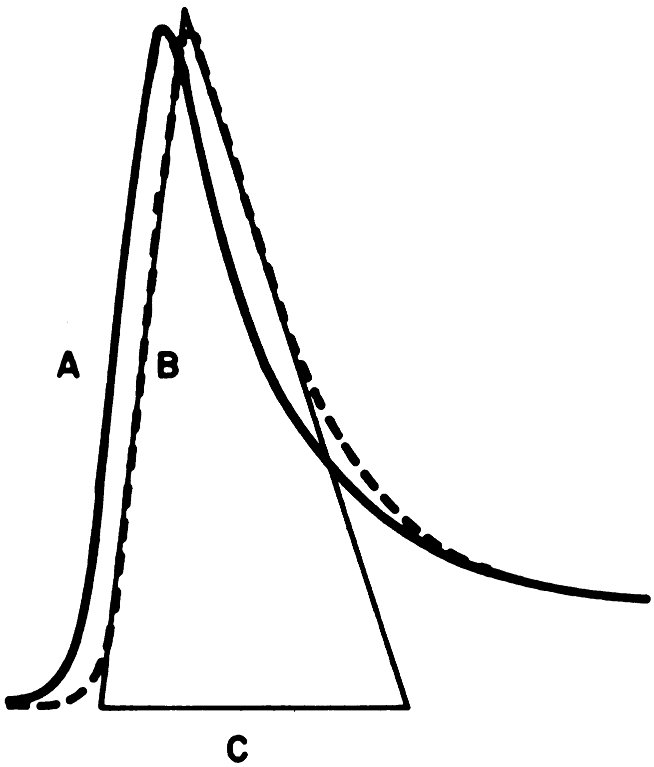

Figure 20. Diagram showing duplicate cardiac output curves recorded two minutes apart in the same animal. The construction of the triangle for determining curve area is shown.

A. Cardiac output = .427 1/min
B. Cardiac output = .425 1/min
C. Triangle for curve area determination

little change in SV was reported. Generally, peripheral vascular resistance has been reported to decrease 10%.[55] Changes in this study ranged from a 1% increase to a 20% decrease in TPR. Beaton[7] listed a 39% decrease in cats receiving 1.5% halothane. Mean arterial pressure was depressed 30-45% in this study. The literature indicates a decrease of 30% in MAP.[55] Sawyer[55] reported a 44% decrease in MAP in swine anesthetized with 1.1% alveolar halothane. Therefore, changes in CO, SV, HR, TPR, and MAP can be related to halothane anesthesia. Usually MVP was increased immediately following induction and then returned toward control. This can be explained by higher halothane concentrations post-induction. Myocardial depression related to halothane would cause increases in MVP.

Other variables also changed within predictable limits. P_aO_2 was increased 300-450% as would be expected when breathing 100% oxygen,[18] but oxygen saturation of hemoglobin changed relatively little. This is explained by the effects of pH on an oxyhemoglobin dissociation curve.[18] End-expired CO_2 increased 10-42% above control for all groups. This was related to lower than normal[33] control values due to hyperventilation during control measurements. Mean values for end-expired CO_2 and P_aCO_2 were very close. In man, the reported difference is 4.6 ± 2.5 mm Hg with P_aCO_2 being higher.[44] In this study, mean values were acceptably close but individual cats occasionally had end-expired CO_2 values that were 10 mm Hg or more different from P_aCO_2 indicating error in end-expired CO_2 measurement. Arterial pH values were depressed approximately 1-2% indicating metabolic acidosis since mean P_aCO_2 was near normal. Base deficit values were 26-85% above control further substantiating the presence of metabolic acidosis and depletion of bicarbonate ion. Finally, respiratory rate generally decreased in animals maintained with the pediatric circle and Ayre's T-piece systems but remained at or above control in the adult circle group. This could indicate increased respiratory effort[68] to maintain normal CO_2 values. Clappison and Hamilton[15] reported increased minute and tidal volumes in human beings after addition of external dead space. The use of the three anesthetic systems allowed comparison of their clinical utility in the cat. The Ayre's T-piece was the most maneuverable and anesthetic levels were rapidly stabilized. This was indicated by inspired and end-expired halothane concentration differences at 15 minutes post-induction as seen from data in Tables 3, 5 and 7 and Figure 10. The other two systems had greater differences for these halothane concentrations indicating loss of anesthetic to the rubber goods.[23] Lower flow rates of these two systems allowed dilution of inspired gases with expired gases. The two circle systems appeared equally adequate for clinical use. However, reports by Hunt[35] and Ver Steeg and Stevens[68] would indicate that the pediatric system should be preferable for small animals. Finally, respiratory rate was more easily monitored in the pediatric circle group and the Ayre's T-piece group than in the adult circle group due to the smaller volumes of the systems and rebreathing bags. A smaller reservoir bag would allow improved monitoring using the adult circle.

As an experimental animal, the cat was adequate for this study. However, placement of arterial and venous implants was often hampered by the small caliber of vessels and induced vasoconstriction. Animals tolerated implants well and were readily anesthetized by mask induction. In conclusion, the cat was an acceptable animal for this study and should be usable for similar studies requiring small experimental subjects. The cat may not show the same cardiopulmonary changes as other species. However, in this study effects on acid-base balance were similar to those seen in babies.[27,48] These cats were able to maintain a normal P_aCO_2 on all systems which may not be true of all species.

This study showed small physiological differences in the cardiovascular and pulmonary variables measured in cats maintained on a pediatric circle system, an Ayre's T-piece and an adult circle system. All changes in these variables can be related to halothane-O_2 anesthesia since all groups had similar control values and no other drugs were utilized. Therefore, the choice of anesthetic systems for small patients is still related to economy, simplicity, resistance to respiration, and personal preference. For maintenance of anesthesia in cats, the author's personal preference is the Ayre's T-piece system. This system is inexpensive, can be adapted for use with almost any anesthetic machine, is not bulky and can be used for mask induction. It does not induce resistance from valves and soda lime. Also, the Ayre's T-piece adds less external dead space than circle systems. In the author's clinical experience, the Ayre's T-piece has provided more stable anesthesia, easier monitoring and faster recovery than the adult circle system.

SUMMARY

Cardiopulmonary variables were measured and differences were evaluated for three groups of six cats anesthetized with halothane in oxygen. The groups varied only in the system used for maintenance of anesthesia and in the total oxygen flow to the systems. Group I was maintained on a pediatric circle CO_2 absorption system with an O_2 flow of 0.5 l/min, Group II was maintained on an Ayre's T-piece system with an O_2 flow of 3 l/min and Group III was maintained on an adult circle CO_2 absorption system with an O_2 flow of 0.5 l/min. Cardiac output, cardiac index, stroke volume, heart rate, peripheral vascular resistance, arterial pressure and venous pressure were the cardiovascular variables measured. Respiratory measurements included end-expired halothane, respiratory rate, end-expired CO_2, arterial PCO_2, arterial PO_2, arterial pH, oxygen saturation and base deficit. Inspired halothane concentration and temperature of arterial blood were also monitored. Each animal was chronically implanted with femoral artery and jugular vein catheters and with an aortic thermistor probe implanted via a carotid artery for thermal dilution cardiac output determinations. Anesthesia was induced with halothane and O_2 by mask, animals were intubated with endotracheal catheters and end-expired halothane concentration was maintained at 1.4%. Control measurements were recorded immediately prior to anesthesia induction and measurements were recorded every 30 minutes over a 135 minute period.

Control measurements were similar for all variables for the three groups. Cardiovascular and respiratory variables were not statistically or clinically different for the three groups. Changes from control in each group were related to halothane anesthesia. The conclusion of this study was that the three systems tested were not significantly different based on the variables measured during halothane-O_2 anesthesia in healthy cats.

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