Anesthesia Machines and Breathing Systems: An Evolutionary Success Story

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Summary

The first anesthetists delivered ether and chloroform from handkerchiefs, towels or inhalers, and nitrous oxide from large reservoirs such as bladders. In 1847, Snow devised a temperature-compensated vaporizer that delivered fully saturated ether in air. Clover improved matters in 1877 by adding liquid chloroform to a large measured gas volume to produce a known concentration. Except for the French Ombrédanne ether inhaler, the United Kingdom provided most advances in vaporizer equipment. Delivered concentrations of anesthetic were usually inexact until 1951 when Morris introduced the Copper Kettle vaporizer to deliver a concentration that could be precisely calculated. In the mid-1950s, Cyprane produced the Fluotec, a "variable bypass vaporizer" that allowed the user to set any desired concentration, eliminating the calculations required with the Copper Kettle.

Early nitrous oxide anesthesia produced insensibility partly from hypoxia. In 1868, Andrews suggested adding oxygen, but no convenient method to do so was available until the 1880s when steel cylinders to contain liquid nitrous oxide and compressed oxygen enabled the delivery of roughly controlled nitrous oxide concentrations. Flowmeters were needed. Cotton and Boothby devised a sight-feed device for visualizing gas flow. In 1913, Gwathmey adapted this as a bubble flowmeter, and Heidbrink improved this device. In 1908, Kuppers introduced what became the primary method of measuring gas flow for most of the twentieth century, the rotameter. In the twenty-first century, electronic flow control replaced the rotameter.

Anesthesia breathing systems replaced simple inhalers. Anesthesia providers increasingly used carbon dioxide absorption systems to minimize delivery of expensive or explosive anesthetics. Water's to-and-fro system competed with the circle system suggested by Jackson in 1916. In 1926, Dragerwerk of Germany developed the first circle breathing system for use on their anesthesia machine. In 1954, Mapleson classified and clarified the function of breathing systems without absorbents. Perhaps the most important development shaping today's anesthesia machines was the 1979 adoption of an anesthesia machine standard written jointly by clinicians and industry engineers. This standard eliminated potential dangers with previous machines.

For many years, anesthesia machines and monitors were sold separately. Displays, controls and alarms of different devices varied, predisposing to confusion and difficulty in management. In the 1990s the distinction between anesthesia machine, ventilator and monitors started to blur. All were integrated into an "anesthesia workstation" so that all modalities were controlled and displayed consistently and in one place, with alarms coordinated and prioritized. Anesthesia delivery systems continue to evolve in ways that improve safety.

Introduction: Early Inhalers

On 16 October 1846, William Morton conducted the first successful public demonstration of surgical anesthesia [1]. That demonstration had two crucial elements. The first was ether's miraculous anesthetic effect. The second was a device that delivered ether in concentrations sufficient to produce anesthesia without killing the patient. The original device (Fig. 52.1) was a glass globe with two necks. The patient breathed in from a brass tube attached to one neck and air entered through the other. The globe usually contained a sponge soaked with ether [2]. The sponge restrained the liquid within the globe—otherwise if tipped the wrong way, the patient might inhale liquid ether. Completing the device were two leather valves in the brass tube, directing the flow of the ether-containing air to the patient, and diverting the expired breath into the room.

Morton's carefully made device (he was late for the first demonstration because his instrument maker was adding last-minute improvements) provided no way of accurately

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Fig. 52.1 This replica of Morton's Inhaler shows the reservoir (globe) that contained the ether. The mouthpiece is to the left. A sponge was often placed in the globe, increasing the surface available for vaporization, but more importantly holding the ether so that liquid anesthetic would not be inhaled. (Courtesy of Wood Library-Museum of Anesthesiology, Park Ridge, IL.)

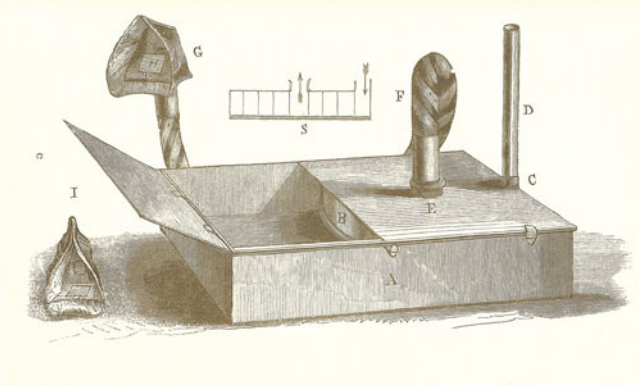

Fig. 52.2 Snow's Inhaler. The air inlet was on the peripheral side (at the right). The drum contained a metal spiral with five turns. This allowed the air to become saturated with anesthetic vapor. Note the wide bore tube which extended from the center to the patient mask. (From Snow J: On the Inhalation of the Vapour of Ether in Surgical Operations: Containing a Description of the Various Stages of Etherization, and a Statement of the Result of Nearly Eighty Operations in Which Ether Has Been Employed In St. George's and University College Hospitals. London: John Churchill; 1847. pp 1–88.)

controlling the ether concentration inhaled by the patient. It was made of glass, a poor conductor of heat. Cooling of the ether caused by its vaporization decreased the delivered concentration. Morton had little or no understanding of the physics involved. This limitation did not apply to the next character in our story.

News of the discovery of anesthesia quickly reached Britain. Physician John Snow appreciated the great significance of the discovery and set out to apply it in his practice. Unlike Morton, Snow understood the physical principles needed to deliver a controlled concentration of ether (or chloroform) and in 1847 constructed an elegant ether inhaler (Fig. 52.2). Air entered the vaporizer and passed through a metal spiral to maximize contact between the air and the ether, thus ensuring a saturated output (i.e., a constant output if the temperature was held constant). Snow immersed the vaporizing chamber in a water bath, to stabilize the temperature. He added a crude means (see below) to dilute the concentration delivered to the patient and connected the vaporizer to the patient with tubing of sufficient width to minimize resistance to breathing. This tubing was connected to a mask edged with leather that molded to fit the patient's face. Some of these features in Snow's vaporizer applied principles used in modern vaporizers.

Snow's vaporizer allowed administration of a constant maximum concentration of anesthetic, useful for induction of anesthesia with ether, the agent for which it was originally devised. The high solubility of ether in blood limited the rate at which induction could be accomplished, and although high concentrations could irritate the airway, they hastened the process. Induction was the principal focus because early in the history of anesthesia, most operations were brief. The introduction of chloroform changed things. Airway irritation was minimal. Unlike ether, chloroform profoundly depressed the heart, making it important to not deliver a maximum concentration for too long. Snow solved this problem by adding a valve on his facemask that could be opened to dilute the delivered anesthetic with room air. Still, control over the delivered concentration was crude.

Joseph Clover solved some of these problems but added others. In 1877, he invented an "inhaler" for chloroform. By putting a measured amount of liquid chloroform into a large reservoir bag of known volume, he could produce a large amount of chloroform vapor in air at a known concentration. The bag was connected to a face mask, including a leaflet valve that allowed exhalation into the operating room. Air could be admitted from the room (thereby diluting the chloroform concentration) by turning the leaflet to the side. Interestingly, the mask and bag connectors had 22 mm diameters, the dimension used today and one that did not impose significant resistance to breathing. Unfortunately Clover's device was cumbersome and had limited popularity. Clover died in 1882 and was buried 200 yards from Snow's grave. One wonders what conversations they have when all is quiet.

Nitrous Oxide

Horace Wells had failed in his January 1845 attempt to demonstrate the anesthetic properties of nitrous oxide. The audience ridiculed Wells, calling the demonstration a humbug, and for nearly two decades nitrous oxide lapsed into obscurity. Gardner Colton resurrected nitrous oxide in the early 1860s. He gave it to more than 100,000 patients for dental procedures without, it is said, a fatality–a remarkable record.

Several problems surrounded the early use of nitrous oxide. First, in normal patients, the anesthetizing partial pressure exceeds atmospheric pressure. To achieve anesthesia, the earliest users administered 100 % nitrous oxide, a lethal concentration if given for more than a minute or two because of the associated lack of oxygen. Nonetheless, nitrous oxide in air or occasionally 100 % nitrous oxide for induction was used until the 1940s, with anesthesia resulting from a combination of nitrous oxide and hypoxia.

Second, because nitrous oxide was a gas, it could not be conveniently stored. It could be manufactured on the spot by heating (with great care, as the process could result in an explosion) ammonium nitrate in a retort [3]. The resulting nitrous oxide was purified by washing it in various reagents and stored in a reservoir—at first a bag made from oiled silk or animal bladders, and later in a gasometer (a small version of the enormous cylinders we see that are used to store natural gas). In 1865, the SS White Dental Manufacturing Co of Philadelphia made a storage bag. A valve was attached to the bag to control the release of the gas to the patient through a wooden mouthpiece. The patient held the mouthpiece with one hand while the nostrils were held closed with the other hand or a nose clip, in order to prevent air dilution. The clumsiness of this system limited its popularity.

The development of low pressure compressed gas cylinders in 1868 decreased the clumsiness; away with the cumbersome bladder/bag. In 1870, nitrous oxide was liquefied. Liquid nitrous oxide was supplied in cylinders by both Coxeter and Son, and Barth in Great Britain. By 1873, Johnson Brothers of New York were supplying similar cylinders to the American market. An attachment to the cylinder led to a large reservoir bag attached to a mask [4]. There was a supplemental bag, a valve to admit nitrous oxide directly into the mask, and an evacuation valve.

Why were these considerable efforts made, to overcome the difficulties and limitations imposed by the large volumes of nitrous oxide needed to provide anesthesia? Nitrous oxide offered two advantages over the then-popular ether: it acted quickly and didn't irritate the airway. These properties complemented those of ether, reducing the slowness and untoward respiratory effects of ether, which were particularly problematic during induction. Around 1876, Clover designed a portable apparatus to deliver nitrous oxide and ether. A nitrous oxide cylinder supplied gas to an ether vessel (vaporizer) with a 6 liter bag connecting the vaporizer to a mask. Air or the nitrous oxide-ether combination could be admitted to the bag. Inadequate oxygen (hypoxia) evidenced by cyanosis caused the patient to breathe more, accelerating the uptake of anesthetic. When marked cyanosis occurred, fresh air was admitted by lifting the face mask.

A few perceptive people recognized the problems imposed by the lack of oxygen. It is not known when oxygen was first used with chloroform, but Snow used it in an unsuccessful resuscitation of a patient given chloroform. In 1868, Edmund Andrews, a Northwestern University surgeon, suggested adding oxygen to nitrous oxide. So did Paul Bert and Clover. In 1879, Bert combined 15 % oxygen with 85 % nitrous oxide to produce anesthesia in a pressure (hyperbaric) chamber. But such an approach was a logistical nightmare. A more practical solution was to go back to a combination of nitrous oxide, oxygen, and ether (called gas, oxygen and ether or GOE). Such a solution was not practical before 1885 when oxygen became available in cylinders. But GOE was not immediately adopted because the importance of using oxygen with nitrous oxide was not widely appreciated until after the turn of the twentieth century. Anesthesia providers continued to use nitrous oxide and air, not recognizing the potential negative effect on patient intelligence.

The availability of both nitrous oxide and oxygen in cylinders meant that large volumes of each could be stored efficiently, and this allowed development of apparatus delivering both. In 1886, Viennese dentist HT Hillischer produced the first machine dispensing both nitrous oxide and oxygen and coined the term "Schlafgas" (sleeping gas) to describe nitrous oxide. He found it best in most cases to commence with 10 percent oxygen/90 percent nitrous oxide, and to gradually increase this to 15 or even 20 percent oxygen. In dealing with alcoholic subjects and others resistant to the influence of nitrous oxide with 10 percent oxygen, he reduced the oxygen to 5 percent or even lower. If breathing became labored, or cyanosis appeared, he increased the percentage of oxygen. Hillischer used a proportioning valve to achieve the target percentages of oxygen. But his proportioning valve was a crude device. Something better was needed.

In 1885, SS White patented what today's clinicians might recognize as an anesthesia machine. Gases were supplied from cylinders to separate inflatable bags then directed to a mixing chamber between the oxygen and nitrous oxide controls and delivered to the patient through wide bore tubing. The tap on the nitrous oxide bag needed to be fully opened, and a similar tap for oxygen allowed a variable flow according to uncalibrated gradations on a semi-circular gauge plate. By 1910 the SS White anesthesia machine had yokes for 4 cylinders, and reducing valves (pressure regulators) that decreased the high but variable pressure of gas from cylinders to a lower more constant level [5].

Gas Flow Measurement

Early anesthetic apparatus lacked a means to deliver precisely known flows (and therefore concentrations) of oxygen and nitrous oxide in the gases presented to the patient [6]. In 1902, dentist Charles Teter developed a gas machine that delivered a variable mixture of oxygen and nitrous oxide, each controlled by separate but coarse valves. There was no indicator of percentage or flow [7]. In 1916, after observing the principles of a mercury sphygmomanometer, Teter added mercury columns to his machine, calibrated to indicate gas flows.

Another dentist, Jay Heidbrink, purchased one of Teter's machines in 1906, and set about improving it. He reasoned that better accuracy could be achieved by equalizing the pressure in the two bags supplying gas from the cylinders to the adjustable valves, and that the valves could be engineered to give finer control. An additional problem was moisture in the nitrous oxide, which often led to freezing of the nitrous oxide valve. Heidbrink solved this by placing an electric light bulb in the mixing chamber. Still, the machine had no indicator of gas flow. He achieved an acceptable calibration of flow control by adopting commercially available pressure-reducing valves and further refining the control valves. His first commercial machine was the Model A, introduced in 1912. He sold them for $1 per pound weight, $32 each.

In 1911, Frederick Cotton and Walter Boothby developed the first anesthesia machine that provided a visible indication of the rate of flow of nitrous oxide and oxygen. Each gas was fed separately into a water-filled glass mixing chamber. The rate of bubbling in the "bubble bottle" allowed an estimation of the flow and proportion of the gases. After exiting the first mixing chamber, a portion of the gas mixture could be directed through another chamber containing ether before rejoining the main gas stream.

In the following year, James Gwathmey improved on Cotton and Boothby's idea by placing "bubble tubes" for each gas within the water sight feed bottle. Each tube had five holes, allowing from one to five streams of bubbles to be seen, thus indicating the gas flow. This was the forerunner of the 1917 Boyle apparatus, developed by Henry Boyle after meeting Gwathmey and purchasing one of his machines in 1912. James Gwathmey was one of the first physicians to practice anesthesia full time. He was president of the New York Society of Anesthesiologists, the forerunner of the American Society of Anesthesiologists.

Richard von Foregger (1872–1960), was born in Vienna, studied chemistry and emigrated to the US in 1898 [8]. In 1905, he began development of an oxygen generator using "oxone" or fused sodium peroxide. In 1907, he met Gwathmey, by which time the oxygen generator was a commercial success. In 1909, they produced an ether-oxygen device using an oxygen generator. On several occasions, Foregger and Gwathmey took the generator to Madison Square and administered oxygen to runners in 10-mile relay races and 6-day bicycle races. In 1914, Foregger established the Foregger Company and began manufacturing Gwathmey's anesthesia machines.

Foregger later developed the water depression flowmeter A competing CIG flowmeter is shown in Fig. 52.3. Gas flowing past a restriction in the top of the flowmeter depressed the water level in a tube submerged in a water-filled container, in proportion to the gas flow. This worked well as long as the flow did not exceed that which produced the maximum intended depression of the water level in the tube. Flows exceeding that limit forced gas into the water-filled container with a violence that depended on the flow. In some training programs no resident entered the "anesthetic brotherhood" until he had fully opened the oxygen valve to the flowmeter, blowing water all over the operating room.

Fig. 52.3 In these CIG water depression flowmeters, the water meniscus was at the black line just above the mark indicating a 1 liter per minute flow rate when there was no gas flow. Flow depressed the meniscus non-linearly, with the greatest change occurring at the higher flows (the opposite of what might be desired)

Dry Flowmeters

Karl Kuppers in Germany, introduced the rotating bobbin flowmeter, the "Rotamesser", in 1909 for industrial purposes, and gynecologist Maximillian Neu used it in an anesthesia apparatus in 1910 [9]. It went into commercial production, but did not become widely known. Rotameters were not used again until 1937, when once more they were adapted to anesthesia machines, this time in Britain.

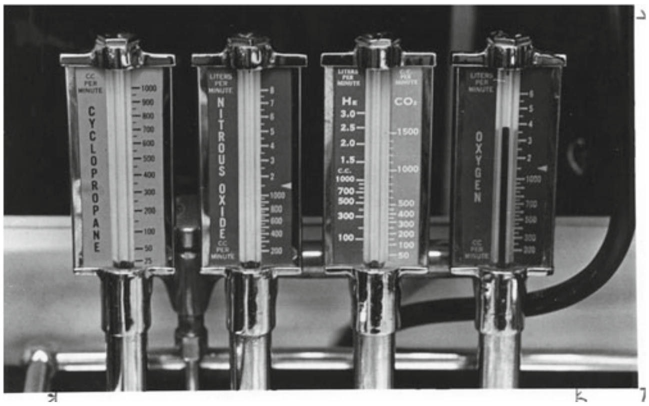

Fig. 52.4 As shown on the oxygen flowmeter on the right, gas flow through these Heidbrink flowmeters caused the indicator to rise in the tube. Note that one flowmeter (flowmeter number 3 in the illustration) could be used for either helium or carbon dioxide

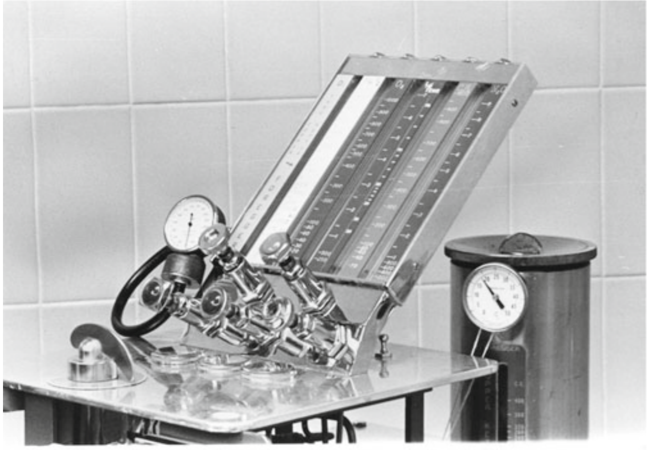

Fig. 52.5 In Foregger and Connell flowmeters one or two balls rose with increasing flow, and the flow was read at the juncture of the two balls. At the right is a Copper Kettle vaporizer. At the front of the machine is the on-off valve that controlled flow to the vaporizer. The flowmeter for the Copper Kettle is at the left. Note the thermometer at the top of the Copper Kettle

American anesthesia providers working in British hospitals during World War II gained experience with rotameters and recognized their advantages. They were first used in American machines in 1950 by Foregger, and quickly became the gold standard for measuring gas flows.

In 1933, Heidbrink invented a tapered tube flowmeter (Fig. 52.4; really a variant of the rotameter), where a disc was attached to a stem, the disc rising in the tapered tube with increasing gas flows, the tip of the stem indicating the flow on a calibrated scale. It presented a graded visual display of flows for oxygen and nitrous oxide, the gases merging as they exited from the flowmeters. An improved version appeared on his Heidbrink machine in 1938.

The Coxeter dry bobbin flowmeter (1933) consisted of a glass tube of uniform diameter with 24 small holes in the wall. An H-shaped bobbin in the tube rose with increasing gas flow, the flow exiting the tube through the holes. As flow increased, the bobbin rose and more gas left the tube through the holes. This flowmeter was relatively inaccurate because friction or dirt between the bobbin and the wall impeded the rise or fall of the bobbin. Since the bobbin moved in steps from hole to hole, it could not measure intermediate flows, and was inaccurate at low flows. These flowmeters were used in the 1933 Boyle machine that was the forerunner of the modern anesthesia machine. It is said that Boyle placed the oxygen flowmeter on the left because he was left handed. Machines manufactured in the US placed it on the right.

The Connell flowmeter was patented in 1934. The six-inch flow tube contained two ball bearings that rose with increasing flow inside a tilted glass tube with a tapered bore. Two ball bearings were needed to ensure steady movement and prevent each ball from oscillating in the tube. Gas flow was noted by the point where the two balls touched. Foregger also marketed a flowmeter that was inclined at an angle and used a ball indicator (Fig. 52.5). It also had shape-coded flow control knobs.

Ultimately, the rotameter became the most popular means of measuring gas flow in anesthesia, appearing on virtually all anesthesia machines up to the end of the twentieth century, when electronic measurement devices and displays replaced tapered tubes.

Intermittent Flow Machines: A Digression

The machines described above delivered a constant flow of gas, much of which was wasted [10, 11]. Intermittent flow machines were devised to decrease this waste, and supply only what the patient needed. They delivered a controlled mixture of gases in a volume "demanded" by the spontaneously breathing patient. They featured a mixing device for oxygen and nitrous oxide. The McKesson Nargraf machine (see Fig. 6.3) was the most popular. It could be set to deliver an oxygen percentage from 0 % to 100 %. The negative pressure generated by the patient during inhalation initiated gas flow from the machine. The flow ended when the patient stopped inhaling. A one-way valve at the patient end of the breathing system opened, so that exhalation to the room could occur.

One of McKesson's techniques, referred to as secondary saturation, used 100 % nitrous oxide until severe cyanosis and muscular rigidity or spasm appeared. Oxygen was then added to the inhaled mixture. It was an exciting approach to anesthesia, but most anesthesia providers preferred not to bring their patients so close to death. Also, it was difficult to deliver a potent anesthetic [12]. Of note, with this apparatus and technique, anesthesia with halothane could be induced in 11 seconds. There is much more to the McKesson history, including the fact that the McKesson Nargraf machine in 1930 incorporated automated anesthesia record keeping.

The Evolving Anesthesia Machine

Anesthesia machines began to take the form initiated by the Boyle machine. In early machines, the Boyle bottle and direct-reading vaporizers like the Fluotec could be placed in the tubing between the machine outlet and the breathing system. If the gas flow in the fresh delivery tubing from the machine was attached (incorrectly) to the outflow connection to the vaporizer, a higher-than-expected output could result. In addition, these vaporizers handled the high flow from the oxygen flush poorly. Coxeters, the manufacturers of the Boyle machine, continuously modified and improved it. By 1927, the rubber hoses had been replaced by a large bore rigid tube between the flowmeters and the vaporizers. Later, the whole apparatus was incorporated into a table on wheels. The Boyle configuration persisted until the 1990s when major changes in anesthesia machines began to appear.

In 1978, Jeff Cooper and his colleagues at the Massachusetts General Hospital exhibited a completely computer-controlled anesthesia machine (the Boston Anesthesia System or MGH machine) [13]. It was never used for humans but was the first to suggest that a computerized machine was possible. In the 1990s anesthesia machines began to incorporate microprocessor-based technology. Computerized ventilators allowing the choice of various ventilatory modes appeared on many machines, and computer-controlled flowmeters working from flow sensors began to replace the rotameter.

Vaporizers

As noted earlier, Snow devised a vaporizer/inhaler for ether that incorporated many features present in modern vaporizers. They included a spiral gas passage to ensure saturation of gases flowing through the vaporizer, and a water bath surrounding the vaporizer to provide better temperature stabilization. Snow differed with another anesthetic great, Sir James Simpson, who said that simpler was better, that a few drops of chloroform on a handkerchief sufficed, and all that complicated apparatus was unnecessary. Simpson's simplistic view often prevailed in the early days of anesthesia. Anesthesia was frequently delivered by a handkerchief or a more sanitary variant that used a gauze placed over a wire frame, such as the Schimmelbusch mask (Fig. 52.6), into the 1950s.

Fig. 52.6 This Schimmelbusch Mask was used to administer ether or chloroform. A gauze or handkerchief was placed over the wire frame and liquid anesthetic dripped onto it. One problem was that as fluid was poured onto the gauze or handkerchief it flowed down to the sides, leaving a dry patch through which the patient breathed. The rim served as a trough to catch surplus fluid

For a time, Snow's ideas were largely forgotten. Apparatus for vaporizing liquid anesthetic agents was crude and inexact. Of necessity, the anesthesia provider's observations of the patient's anesthetic depth (e.g., Snow's degrees and Guedel's signs and stages of anesthesia) were used to determine the amount of anesthetic to deliver.

In 1902, Dragerwerk developed a drip feed injector to administer ether or chloroform. The drops could be counted and thus the volume of agent added to the gases breathed by the patient could be calculated. But who had time to count the drops and then calculate (taking into account the flow of diluent gases) the actual concentration of anesthetic inhaled by the patient? Observations of the patient's clinical signs still governed the amount of anesthetic delivered.

A Parisian surgeon, Louis Ombrédanne, introduced a new ether inhaler in 1908 [14]. He criticized previous inhalers "*….as these are not provided with means of admission of fresh air, they rapidly produce cyanosis if one does not constantly raise the mask from the face*." Ombrédanne's inhaler/vaporizer avoided delivery of hypoxic gas mixtures by admitting air. It became the most commonly used apparatus for ether delivery in France and Latin America, and aided in the conversion from chloroform to ether. It continued to be used for a half century.

The Boyle Bottle (Fig. 52.7) appeared in 1917, and consisted of a glass bottle (the vaporizing chamber) that held the liquid anesthetic (any could be used). A controllable fraction of the gas to be delivered was diverted through the bottle, which was fitted with a plunger and cowl that could direct the gas flow close to the surface of the liquid—or under the liquid surface, resulting in a greater amount of agent being vaporized. Heat loss occurred during vaporization, and the decreased temperature decreased vaporization of the liquid anesthetic, and thus the concentration added to the diverted gases. The anesthesia provider often placed a pan of hot water around the outside of the bottle (there was a formal arrangement that permitted this to be done easily) to warm it, but the

Fig. 52.7 Rotameters were used on this Boyle machine. Gas issued to the right of the flowmeter bank through valve-levers that could direct none to all of the flow through each of the two glass Boyle bottles (one here for halothane and the other for ether) in series to its right. In this photograph, the levers are down (off). Vaporization could also be increased by lowering a plunger that forced the gas directed through the vaporizing chamber to bubble through the liquid anesthetic

Fig. 52.8 Ohio #8 bottles were placed in the breathing circuit, usually on the inspiratory side. The gases flowing past the vaporizer could be diverted through the glass bottle by rotating the lever atop the vaporizer. The amount of gas diverted was proportional to the degree to which the lever was turned. Note the wick used to increase vaporization. As with the Boyle bottle, one could increase or decrease the amount of anesthetic administered (by increasing or decreasing diversion), but the resulting concentration delivered to the patient was unknown

bottle was composed of glass, a poor heat conductor. Snow also incorporated a pan of water around his vaporizer, but he made his vaporizer of copper, a good conductor of heat. The anesthesia provider using the Boyle Bottle could not know the concentration of anesthetic delivered. The patient's clinical signs guided how much should be administered.

The Boyle bottle could be placed inside a rebreathing absorption system ("in-circuit"), but was normally outside the system or used with a non-absorption system (no carbon dioxide absorption by soda lime). Simpler versions of the Boyle bottle with small liquid capacities (Rowbotham, Goldman) were used in British circle breathing systems.

The Ohio #8 bottle (Fig. 52.8) was one of the most popular in-circuit vaporizers in the 1940s and 1950s in North America. Its sister, the Goldman, was used throughout the rest of the world. Both were glass bottles containing a wick to maximize the surface available for vaporization of the liquid anesthetic, usually ether. There was no way to provide temperature compensation. A control dial atop the vaporizer allowed the anesthesia provider to divert any proportion from none to all of the inspired gases through the vaporizing chamber. Since this was an in-circuit vaporizer, some anesthetic vapor returned to it during the next inspiration, adding to the imprecision of vapor delivery. This could be dangerous because vaporizer output was directly tied to minute ventilation, and lethal concentrations of anesthetic could be delivered, especially with controlled ventilation. This device was especially dangerous when used with a potent volatile anesthetic having relatively low blood solubility and a relatively high vapor pressure such as halothane. Again, the patient's clinical signs were used to guide the amount of anesthetic delivered. Exhaled gases contain water vapor, and when passing through the vaporizer the water would dissolve in the liquid anesthetic. Large amounts of water can dissolve in ether. The ether would be diluted and its vapor pressure lowered, limiting the level of anesthetic that might be achieved at a particular setting of the indicator dial.

In the 1950s, a major advance occurred with the development of the Copper Kettle vaporizer by Lucien Morris [15]. This change was so important that Chapter 53 in this book is devoted to this invention. The Copper Kettle vaporizer was the first to deliver a known output of anesthetic at any flow rate or vaporizer temperature. As with the Boyle bottle, any liquid anesthetic could be used. There were two gas flows. One was independent of the vaporizer (the diluent or bypass flow), and the other was the flow through the kettle. The kettle containing liquid anesthetic was made of copper attached to a copper tabletop (hence the name). Copper was chosen because of its high thermal conductivity, allowing the temperature (and therefore the vapor pressure) of the liquid anesthetic within the kettle to remain relatively constant (as in Snow's inhaler—at last someone listened). The anesthesia provider knew the flow to the kettle and its temperature from a thermometer in the vaporizer wall. Assuming that the gas exiting the kettle was fully saturated with anesthetic, calculation of the added volume of anesthetic was possible. For example, if 100 ml of gas were directed to a kettle containing halothane, then the exiting gas would contain 33 % of an atmosphere of halothane (its vapor pressure) and the volume of halothane vapor would be 50 ml (i.e., $50/(100+50)=0.33$ or 33 %). Add this to a diluent flow of 5,000 ml and the delivered concentration approximated 1 %. Vapor output remained constant with the Copper Kettle.

Most clinicians were accustomed to the concentration decreasing as the liquid cooled, and sometimes were surprised to achieve a greater-than-expected anesthetic depth when using the Copper Kettle.

Ohio Medical Products Corporation soon marketed a vaporizer called the Vernitrol that was similar to the Copper Kettle. Two Vernitrol's (for two anesthetics, perhaps halothane and ether) could be placed on an anesthesia machine, each with its own flowmeter. Copper Kettle and Vernitrol vaporizers continued in common use until the 1980s. The Ohio DM 5000 anesthesia machine, introduced in the late 1960s, featured the last of the kettle-type vaporizers. The vaporizer was heated to maintain a constant temperature and provide an accurate agent concentration. On this machine, the vaporizer flowmeter indicated ml of vapor emanating from the vaporizer rather than ml of oxygen going into the vaporizer, as was the case with the Copper Kettle. If the same calculations as those for the Copper Kettle were used with the DM 5000, the patient would receive a much higher anesthetic concentration. Having a mix of machines within an OR suite sometimes resulted in anesthesia providers moving from one operating room to another without realizing that the output of the vaporizer was double or one half of that in the room from whence they came. This resulted in several deaths and a number of cases of patient awareness. Some anesthesia providers called the DM 5000 "the widow maker".

In the 1950s, Cyprane in England produced the Fluotec vaporizer (Fig. 52.9), a so-called "variable bypass vaporizer" that allowed the user to directly set the desired percentage of agent—thus eliminating the calculations associated with the Copper Kettle and Vernitrol. Incremental improvements further increased the output stability, so that it remained relatively constant despite variations in fresh gas flow and temperature. It was the first vaporizer designed and calibrated for use with only one anesthetic agent. Other companies also developed direct-reading vaporizers, such as the Foregger Fluomatic and the Dragerwerk Vapor. A potential problem with the Fluotec (and other "Tec" type vaporizers) was that any volatile anesthetic could be poured into the vaporizing chamber. Of course this would result in an anesthetic concentration different than that on the dial—greater if the vapor pressure of the agent was greater than that of the agent for which the vaporizer was calibrated, and vice versa. This problem was partially solved using a keyed system on both the bottle and the vaporizer (see also Chapter 66 on the contributions of industry to the history of anesthesia.).

Desflurane was introduced in the late 1980s. Since it had a boiling point near room temperature, it could not be used in the usual variable bypass vaporizer. This problem could be solved by either cooling the agent to a point well below room temperature, or by heating it to well above room temperature so that the vaporizing chamber delivered 100% agent as a gas. Heating was chosen. An amount of pure vapor, determined by the concentration dial, was added to the fresh gas passing through the vaporizer.

Fig. 52.9 Fluotec Mark II Vaporizer. Note the card chained to the vaporizer with a graph showing how fresh gas flow affected the vaporizer output. A predictable (flat line) output was accomplished at inflow rates of 1–2 l/min or more for this early model. Later versions produced constant known outputs at flows as low as a few 100 ml/min

Until the middle 1990s, vaporizers were mechanically controlled by altering the relative flows through the bypass and the vaporizing chamber. The Physioflex anesthesia machine was the first to use computer control of vapor concentration in a totally closed rebreathing absorption circuit with constantly circulating gas. Using feedback from agent monitors, a computer directed the vaporizer to inject liquid anesthetic directly into the gas stream in an amount sufficient to produce the agent concentration dialed on the anesthesia machine.

A new variable bypass vaporizer, the ADU, became popular in the 2000s [16]. It differed from the "Tec-type" devices in that the output was governed by computer control of the flow issuing from the vaporizer sump and the flow that bypassed the sump, doing so in a manner that produced the output concentration of anesthetic prescribed by the dial setting. This meant that any volatile anesthetic, including desflurane, could be used. The ADU vaporizer was separate from the anesthetic sump. A given sump was specific for a given anesthetic, and when the sump was attached to the vaporizer, the vaporizer recognized the anesthetic by the identity of the sump (oh, those computers!)

Breathing Systems

Systems Without Carbon Dioxide Absorption

The preceding discussions focused on the anesthetic machine, the large and expensive device concocting a mixture of known concentrations at a controlled flow rate. In order to produce anesthesia, this mixture must be transported to the patient. The delivery vehicle is the breathing system with the interface being a mask, a supraglottic airway device (such as the laryngeal mask airway) or a tracheal tube.

Morton, Snow and Simpson used non-rebreathing systems where the anesthetic mixture was inhaled and then exhaled to ambient air. There were exceptions. Patients breathing from bags containing nitrous oxide might rebreathe some of the gas they exhaled. And some of the systems delivering potent vapors did not have valves to prevent rebreathing.

Over the years various other systems developed. In 1954, WW Mapleson analyzed and classified the various systems that did not have carbon dioxide absorption, and suggested the fresh gas flows needed to minimize rebreathing of exhaled carbon dioxide [17]. These seemingly uncomplicated devices had many advantages, being lightweight and relatively simple. Today, however, they have largely disappeared because they required high flows, potentially increasing the cost of anesthetic delivery to $100 per hour or more! High flows also increased contamination of the atmosphere with anesthetic gases and vapors, a matter of rising environmental concern. Some of these systems linger today in the form of the Mapleson D and E systems used for pediatric anesthesia, or to supply oxygen during patient transport or emergency situations when the primary source of anesthesia malfunctions.

Systems with Carbon Dioxide Absorption

In 1903 Dragerwerk developed a device to absorb carbon dioxide from rebreathed gases using soda lime (mostly calcium hydroxide spiked with a bit of sodium and potassium hydroxide). Miners carrying oxygen cylinders used this device underground. Oxygen was added to the breathed gas to make up for the oxygen taken up by the miner. This invention was not immediately applied to anesthesia breathing systems because anesthetics were relatively inexpensive (Crawford Long charged $0.25 for the ether he used to anesthetize James Venable). In addition, chloroform, which was commonly used at that time, reacted with soda lime to produce the nerve gas phosgene.

In 1916, Dennis Jackson demonstrated an apparatus equipped with a device for absorbing carbon dioxide, but he used a solution of alkali, an approach difficult to apply in practice. In 1923, Ralph Waters introduced a breathing apparatus with an absorber between the reservoir bag and the fresh gas inlet (Fig. 52.10) [18]. The absorber contained soda lime, and although this "to-and-fro" system worked, it was cumbersome and became progressively less efficient (absorbed less carbon dioxide) with continued use. Although it remained of academic interest and was buoyed by Waters' great imprimatur, it gradually fell out of favor. It was used as recently as the1970s for patients with pulmonary infections since it could be cleaned easily.

Fig. 52.10 In the to-and-fro system developed by Ralph Waters, the carbon dioxide absorbent was placed in the large canister. The patient breathed back and forth (to and from the reservoir bag attached to the distal end of the canister) through this valveless system. There were two problems with this elegantly simple system: 1) The absorbent at the proximal (patient) end of the canister exhausted first, increasing the dead space. 2) The absorbent tended to settle, resulting in a low resistance pathway at the top of the absorber

In 1926, Dragerwerk of Germany developed the first circle breathing system for use with their Model A anesthesia machine. There were separate hoses for inhalation and exhalation; low resistance, thin mica unidirectional valves that forced the gases to move in a circle; a canister for the soda lime; a reservoir bag, and a pressure-limiting valve—all components found in circle systems today. It also included an absorber bypass to allow deliberate rebreathing of carbon dioxide. The bypass was included in many systems, but caused problems because it was often inadvertently left in the bypass position. As a result, it was removed from circle systems in the US. It was reintroduced in the twenty-first century, to allow the absorbent to be changed during an anesthetic. The risk associated with its being inadvertently left in the bypass position was lessened by the routine use of carbon dioxide monitoring.

For a time, large absorbent canisters were in vogue. Wrongfully, it was thought that soda lime would regenerate since the color indicator (indicating exhaustion of the absorbent) returned to white after a period of non-use. James Elam and Elwyn Brown designed and advocated the use of large absorbers, particularly two large canisters in series [19].

These allowed nearly complete absorbent exhaustion before the upstream canister needed to be changed. The presence of the second canister ensured that no carbon dioxide would be rebreathed.

A controversy arose in the 1990s regarding the reaction of sevoflurane with an absorbent—either Baralyme® or soda lime - to produce a nephrotoxin called compound A [20], and the reaction of several anesthetics (particularly desflurane) with desiccated Baralyme® or soda lime to produce carbon monoxide [21]. These problems led to the development of new absorbents (e.g., Amsorb® in 1999) that, even when desiccated, did not react with the anesthetic [22]. In the early 2000s, several fires and explosions occurred during the use of sevoflurane [23]. The problem was traced to a triple combination of sevoflurane, desiccated but otherwise fresh Baralyme®, and low fresh gas flows. Baralyme® was removed from the market and the problem disappeared.

Scavenging Systems

Before the late 1960s there was little concern about the effects of occupational exposure to trace concentrations of anesthetic gases. Then a report on health problems in Russian workers exposed to anesthetic gases and vapors was published [24]. Investigators from other countries confirmed that there might be adverse effects in anesthesia providers. As a result, devices for scavenging and removing gases from the operating room quickly came into use.

Corrugated Tubing and the Reservoir Bag

Winston Churchill said “Out of intense complexities, intense simplicities emerge.” The anesthetic circuit has evolved by trial and error into a system of considerable efficiency and utility. Some of the principles of the anesthetic circuit have been known since the time of Snow who maintained that significant resistance to breathing should not be imposed by the anesthesia system. Thus the tubing used to conduct gases to and from the patient must be of large diameter. Pictures of early devices do not show a crucial characteristic of modern tubing: corrugation. A corrugated tube resists kinking, and for the better part of the last century, corrugated tubing has been used.

The circle system became more popular after ethylene and cyclopropane were introduced into anesthesia practice, in 1923 and 1934. Exposing these gases to a spark could produce an explosion that could kill or injure patients and clinicians, a disaster that led to the cessation of the use of cyclopropane in Latin America in the late 1930s. To minimize the chance of a spark from a static electric charge, the anesthetic machine and everything connected to it were made conductive. Thus the corrugated tubing and bags were composed of black (carbon) conductive rubber. Anesthesia personnel wore conductive shoes that grounded the clinician to the floor, and wet sheets were draped around the anesthesia machine and operating room table, as well as on the floor, for personnel to stand on to prevent static sparks from being generated. Special non-sparking electrical power switches, using mercury in a sealed glass tube, were used in operating rooms. As the 1960s came to an end, so did use of ether, ethylene, and cyclopropane—and the need for conductive rubber and other measures. Halothane swept all the explosive anesthetics aside and lightweight disposable tubes and bags came into vogue.

And what of the mundane reservoir bag? To best serve the anesthesia provider and patient, it needs to be of sufficient size to hold enough gas to allow deep respiration. In the 1950s, 10 L reservoir bags were available. These were cumbersome, difficult for the anesthesia provider to grasp, and made it difficult to see how deeply the patient was breathing. As Goldilocks would say, the reservoir bag should be not too small, not too large, but just right. And so, today, it is usually three liters for adults, and smaller for children.

Standardization, Information Technology, and Modern Anesthetic Machines

Perhaps the most important development shaping today’s anesthesia machines was the 1979 adoption of the first anesthesia machine standard. Clinicians and industry engineers examined problems with previous machines that could have or did lead to patient mortality and morbidity. The standard aimed to eliminate or warn of serious problems. Some of the requirements in the standard included flowmeters in series instead of in parallel, fluted oxygen flow control knobs for tactile feedback, a means to prevent administration of a hypoxic mixture, and color-coded flowmeters. Machines manufactured after publication of this standard needed to meet all the requirements of the standard.

For many years, anesthesia machines and monitors were sold separately. Buying the “best of breed” equipment for each use allowed healthcare facilities to distribute spending over time. But monitors stacked on anesthesia machines or separate carts were difficult to manage. Cables from different monitors caused what came to be known as the “spaghetti syndrome”, and the whole array was referred to as a “Christmas tree” [25]. The combined collection of devices could turn into a discotheque of buzzers, bells and flashing alarm lights, with important information scattered over the separate units. Displays, controls and alarms of different devices varied, leading to confusion and management problems. In the 1990s, the distinction between anesthesia machine, ventilator and monitors started to blur. All were integrated into an “anesthesia

Table 52.1 Timeline

1846 William Morton publically demonstrates ether anesthesia.
1847 John Snow constructs an inhaler for constant vaporization of ether.
1865 SS White manufactures a storage bag for nitrous oxide.
1868 The Coxeter and Barth companies provide compressed gas in a cylinder.
1868 Edmond Andrews suggests adding O_2 to N_2O.
1870 Cylinders of liquefied N_2O become available.
1877 Joseph Clover invents a chloroform inhaler giving a known concentration.
1879 Paul Bert gives 15% O_2 with N_2O to produce anesthesia in a pressure chamber.
1885 Coxeter of London makes O_2 available in cylinders.
1885 SS White develops the first machine where O_2 and N_2O are mixed in a chamber and then administered to the patient.
1886 Hillischer develops a machine to deliver both O_2 and N_2O.
1886 Gwathmey develops a nitrous oxide-oxygen apparatus with control valves for the gases and a bubble flowmeter.
1893 Hewitt develops a N_2O-oxygen stopcock which becomes available in 1897.
1893 Hewitt's anesthesia apparatus uses cylinders for nitrous oxide and O_2.
1902 Drager develops a drip-feed vaporizer.
1903 Dragerwerk describes the first breathing system with CO_2 absorbent.
1906 Heidbrink develops an O_2-N_2O anesthesia machine.
1909 Kuppers develops the rotameter.
1910 Neu uses the rotameter in anesthesia
1910 SS White anesthesia machine has yokes for 4 cylinders but does not estimate gas concentration or flow.
1912 Boothby develops the bubble bottle flowmeter.
1913 Heidbrink develops the disc flowmeter.
1914 The Foregger Company builds the Gwathmey apparatus.
1916 Dennis Jackson describes a breathing system that absorbs CO_2 using an alkali solution.
1923 Ralph Waters introduces to-and-fro rebreathing systems with CO_2 absorption.
1926 Heidbrink offers the first mass-produced anesthesia machine, the Model A.
1926 Dragerwerk develops the circle rebreathing system.
Late 1920s Foregger develops the water depression flowmeter.
1930 Coxeter dry bobbin flowmeter is developed.
1934 Connell double ball flowmeter is developed.
1950 Rotameters are introduced into US anesthesia machines.
1952 Lucien Morris invents the Copper Kettle vaporizer.
1954 Mapleson categorizes non-rebreathing anesthesia circuits.
1957 Fluotec vaporizer is released.
1978 The Boston Anesthesia System is described.

workstation". These workstations were designed to solve some problems by integration so that all modalities were controlled and displayed consistently and in one place, with alarms coordinated and prioritized. The whole setup could be purchased from and serviced by a single manufacturer.

And what of the future? It seems likely that the anesthesia workstation will someday be part of an information network for the entire healthcare facility. Other tasks, including anesthesia recordkeeping, will increasingly become automated.

Reprise

In the beginning, anesthetists delivered ether and chloroform from various devices ranging from handkerchiefs to inhalers, while nitrous oxide was inhaled from a bladder (see Table 52.1). The inhalers underwent improvements in their control over the delivered anesthetic concentration. Today's vaporizers accurately deliver the anesthetic concentration dialed by the anesthesia provider at any fresh gas flow rate and at any temperature, an achievement attained by the mid-twentieth century. The use of nitrous oxide to complement the action of the potent inhaled anesthetics was delayed for several decades after the discovery of anesthesia in 1846, until a means to efficiently store it and combine it with oxygen (also requiring an effective means of storage) were developed. The needed technology was applied in the latter part of the nineteenth century, and was combined with gas flow measurement to give birth to the anesthetic machine. Gas flow measurement was first accomplished using a water sight flowmeter where bubbles indicated the gas flow. Water depression and dry bobbin flowmeters were replaced by the rotameter. Electronic flow controls replaced rotameters in the twenty-first century.

The machines supplied the anesthetic mixture, but a breathing system was needed for the interface between the machine and the patient. Many early breathing systems were non-rebreathing devices (e.g., open drop delivery of ether or chloroform). Most mask inhalers relied on rebreathing, some to a potentially dangerous level. All these devices released the exhaled gases into the operating room. With the need to minimize delivery of expensive or explosive anesthetics, in the first half of the twentieth century, anesthesia providers turned to rebreathing systems with carbon dioxide absorption—except for anesthetics such as trichloroethylene where the potential for production of phosgene from the reaction of absorbent with trichloroethylene discouraged the use of such absorption. To-and-fro systems competed with circle systems in the first half of the twentieth century, with circle systems winning out. Carbon dioxide absorbents developed in ways that decreased the likelihood of degradation of potent inhaled anesthetics. Other components of the circle system (the corrugated tubing, valves, and reservoir bag) evolved in ways that minimized resistance to gas flow, and unwieldiness. In the latter portion of the twentieth century, concerns regarding the health implications to operating room personnel of breathing exhaled anesthetics led to the scavenging of excess gases.

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