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NARRATIVE REVIEW

Historical development of the anesthetic machine: from Morton to the integration of the mechanical ventilator

Pablo Romero-Ávila [a,*], **Carlos Márquez-Espinós** [b], **Juan R. Cabrera Afonso** [b,c]

[a] *Hospital Costa del Sol, Department of Anesthesiology and Resuscitation, Marbella, Spain*
[b] *Hospital La Línea, La Linea de la Concepción, Department of Anesthesiology and Resuscitation, Cádiz, Spain*
[c] *University of Cádiz, School of Medicine, Department of the History of Science, Cádiz, Spain*

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Abstract The first anesthetic machines appeared following their public demonstration by Morton in 1846. These initial devices were simple inhalers based on the evaporation of the anesthetic agent. Their main problem was the loss of effectiveness with cooling. More complex inhalers were subsequently developed, in which the main difference was the possibility to provide more than one agent. Moreover, the concentration of the inhaled anesthetic was regulated for greater efficiency. At the beginning of the twentieth century, gas machines emerged, allowing the application of an anesthetic flow independent of the patient's inspiratory effort. These machines incorporated technological advances such as flow meters, carbon dioxide absorption systems and fine adjustment vaporizers. In this period, in the field of thoracic surgery, intraoperative artificial ventilation began to be employed, which helped overcome the problem of pneumothorax associated with open pleura by applying positive pressure. From the 1930s, the gas machines were fitted with a ventilator, and by the 1950s this had become a basic component of the anesthesia system. Later still, in the 1980s, alarm and monitoring systems were incorporated, giving rise to the current generation of workstations.

Introduction

The anesthetic machine is one of the most important tools used by anesthesiologists, and understanding its characteristics and functions is an essential part of anesthetic practice.

* Corresponding author.
E-mails: deromeroyavila@gmail.com, deromeroyavila@hotmail.com (P. Romero-Ávila).

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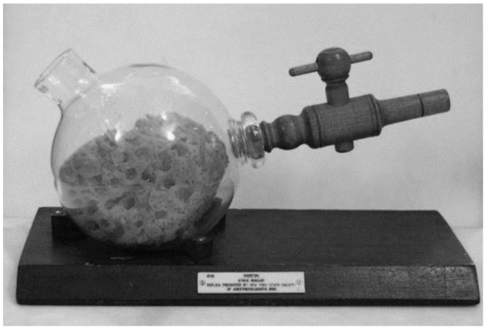

Figure 1 Replica of Morton's inhaler, used in his first public demonstration (October 1846). Courtesy of the Association of Anaesthetists Heritage Center. Reference LDBOC: 1.1.3. Reproduced with permission.

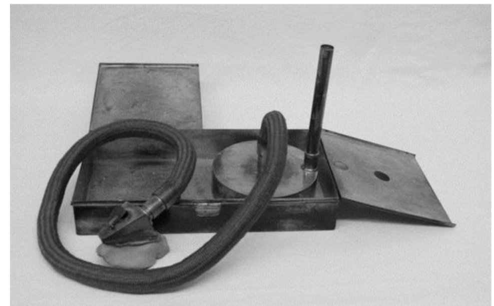

Figure 2 Replica of Snow's ether inhaler. Image courtesy of the Geoffrey Kaye Anesthesia History Museum, Melbourne, Australia. Registration number 4575. Reproduced with permission.

Moreover, this technology is subject to continuous change and innovation, and so professionals must remain up to date in their field.[1]

Generically, the term anesthetic machine, apparatus or equipment is taken to mean the set of elements intended to provide medicinal gases and anesthetics to a patient during an anesthetic act, whether in spontaneous or controlled ventilation.

Anesthetic machines have evolved from simple inhalers to today's work stations, resulting from the integration of the anesthesia device itself with monitoring, alarm, and protection systems.[2] The anesthesia device consists of several components, including gas delivery and evacuation systems, vaporizers, electronic flow meters, and a ventilator.[3]

The purpose of this article is to examine how the main components of the anesthetic machine have evolved, and to describe their gradual integration into a single device, from its rudimentary beginnings until the introduction of the mechanical ventilator.

The first anesthetic devices: simple inhalers (1846-1876)

Morton's ether inhaler (Fig. 1), which was introduced on October 16, 1846 at the Massachusetts General Hospital (Boston, USA), is considered the first real anesthesia device. Although ether had previously been used for anesthetic purposes, it was administered by applying a folded towel, soaked with ether, to the patient's nose.[4,5]

Morton's ether inhaler consisted of a small crystal ball containing a sponge and fitted with two necks. The ether was deposited through one of the necks, and a wooden spout was attached to the other, regulating the passage of gas, and connected at the far end to the patient's mouth.[6] Morton rapidly modified and improved this prototype, and at the public demonstration held the following day, on October 17, he had already incorporated valves in the exit nozzle, as noted by Henry Jacob Bigelow in his letter to the *Boston Medical and Surgical Journal*.[7,8]

News of the success of Morton's public demonstration arrived in Europe in just two months, leading to a boom in the manufacture of anesthesia devices, from late 1846 until mid-1847. These first designs were based on the description of Morton's inhaler made in Bigelow's letter, and resulted in devices such as Squire's ether inhaler, Robinson's ether inhaler, and the Hooper ether inhaler, in England; the Charrière device, in France; and the Dieffenbach inhaler, in Germany.[9]

These devices shared certain common characteristics: they consisted of a glass ether container with an entrance orifice and an exit orifice, which was attached to an intermediate element, a hose or a tube, the other end of which was connected to the patient's respiratory tract. A sponge was introduced into the container to increase the evaporation surface, according to the basic principle of vaporisation.[4]

The technique was significantly advanced with Snow's ether inhaler (1847). John Snow quickly realized that the administration of ether with these original apparatuses was unsatisfactory. He believed it necessary to administer the ether via large gauge tubes, providing sufficient exposure of the application area. Moreover, it was essential to maintain the temperature, and thus the gaseous state of the ether by heating the vaporization chamber. Therefore, he designed his own inhaler (Fig. 2) based on these ideas and including a vaporization chamber inside a tin or copper-plated box, which served as a hot water bath to prevent the ether from cooling when the appliance was in use.[10]

In November 1847, James Young Simpson introduced chloroform into clinical anesthetic practice. For its administration, he recommended pouring some liquid onto a hollow sponge, pocket handkerchief, piece of linen or paper, and placing this over the patient's mouth and nostrils.[11] This recommendation was very well received by surgeons, who were thus freed from the use of cumbersome and sometimes ineffective ether devices, the production of which began to decline. For the next 20 years, anesthesia, whether by chloroform or ether, was commonly administered by the application of a soaked compress, at first, and later via wire cones and masks. In every case, these methods were open or semi-open.[12]

In 1862, Joseph Thomas Clover invented a chloroform anesthesia device which enabled the accurate measurement and administration of mixtures of chloroform and air (Fig. 3), helping avoid the overdoses (sometimes fatal) that had commonly occurred before with this anesthetic.[13] Other devices for chloroform were also developed, such as the Sansom inhaler[14] in 1865 and the Junker apparatus in 1867 (Fig. 4), which had a hand-operated bellows with which to propel the mixture of gases towards the patient.[15]

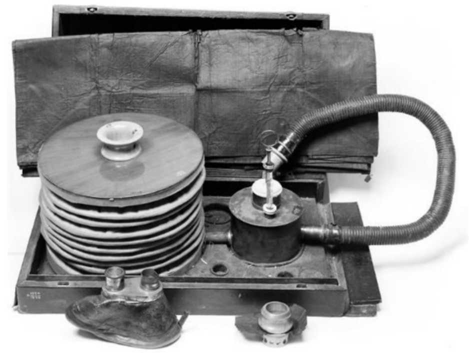

Figure 3 Clover's Chloroform Apparatus (1862). Free access image. Credit: Wellcome Collection. CC BY.

Figure 4 Junker-type inhaler for anesthesia, London, England (1867). Public Domain. Credit: Science Museum, London. CC BY.

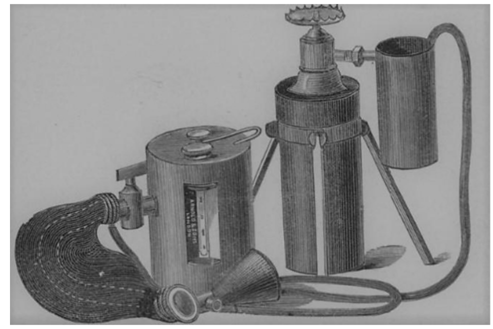

Figure 5 Clover's nitrous oxide/ether apparatus (1876). Manufacturer's catalogue, p. 325. Public Domain. Credit: Wellcome Collection. CC BY.

Figure 6 Clover's portable regulating ether inhaler (1877). Image courtesy of the Geoffrey Kaye Anesthesia History Museum, Melbourne, Australia. Registration number 1792.

However, accidents with chloroform were still commonplace,[16,17] leading physicians to consider other anesthetics and to demand more precise anesthesia devices.

Complex inhalers (1876-1908)

The development of complex inhalers occurred as a consequence of two clinical needs: to adjust the concentration of the anesthetic agent inspired, and to administer more than one inhalation agent.[18]

Nitrous oxide had been known for its hilarious and analgesic properties since the late eighteenth century. The drawback was that its collection and administration required bulky and highly complex equipment, hampering portability and basically limiting its use to dental surgeries, where it was used as a gas analgesic.[19] However, in 1870 both George Barth and Coxeter & Son, working in Great Britain, managed to compress the gas and store it in liquid form in steel cylinders, and in 1873, the Johnston & Brother company did the same in New York.[20,21] This innovation greatly facilitated the use of nitrous oxide in surgical medicine.

In a further development, Clover manufactured a nitrous oxide/ether apparatus in 1876, which was the first attempt to sequence the administration of these anesthetic gases. The apparatus consisted of an ether vaporizer, a steel cylinder containing liquid nitrous oxide, a gas stopcock attached to it, an india-rubber bag and a facepiece (Fig. 5). The vaporizer and the nitrous oxide cylinder were each connected to an intermediate element, which was attached by another connection to the india-rubber bag containing the anesthetic gases, and which in turn was connected to the facepiece. The ether vaporizer could be used alone, or in conjunction with nitrous oxide by activating a tap at the base of the storage cylinder. At the top of the intermediate element, a control key allowed the nitrous oxide to pass through the ether chamber or bridged it to be supplied directly to the patient. Thus, the anesthesia could be induced with nitrous oxide and later maintained with the ether vaporizer, a method that was less disagreeable for the patient.[22]

In 1877, to adjust the concentration of the anesthetic agent inspired, Clover produced a portable ether regulator inhaler. This apparatus consisted of a small spherical metal chamber, partially filled with ether, which was traversed by two concentric tubes, on the ends of which were fitted a rubber bag and a mask, respectively (Fig. 6). By rotating the sphere around the central tube, two apertures in the base were gradually opened and the air breathed by the patient passed over the ether. A small reservoir of water attached to the sphere was intended to attenuate the cooling of the ether as it evaporated.[23] This device was the first to properly regulate the amount of air inhaled, and became very popular in the United Kingdom, where it was in use by RAF medical services until the Second World War.[24]

The incorporation of oxygen into the gas mixture was not considered necessary until the beginning of the twentieth century, although in 1868, Edmund Andrews, a surgeon at Northwestern University, suggested adding oxygen to the nitrous oxide. This recommendation was followed by Paul Bert and by Clover. Thus, in 1879, Bert combined 15% oxygen

Figure 7 Hewitt apparatus for the administration of nitrous oxide and oxygen. Public Domain. Credit: Wellcome Collection. CC BY.

with 85% nitrous oxide to produce anesthesia in a hyperbaric pressure chamber, although this solution remain impractical until 1885 because the technology available was insufficient to store pure oxygen in high-pressure cylinders.[21]

Among the first devices to combine nitrous oxide with oxygen, an interesting example is the apparatus described by Hewitt in 1893 (Fig. 7), which was composed of two nitrous oxide cylinders, an oxygen cylinder, a structure to support and combine the cylinders, a double india-rubber tube (internal and external), a double india-rubber bag, a stopcock and a face mask.[25,26] A notable aspect of this device was the incorporation of a stopcock to regulate the administration of the two gases. This control had positions to administer air, nitrous oxide, or an oxygen-nitrous oxide mixture, in variable proportions.[27]

The introduction of pressure-reducing valves greatly improved the performance of the anesthetic machines, allowing the operator to reduce high pressures within the cylinder, by varying degrees, to a constant, low outlet pressure, even when the pressure inside the cylinder had fallen from 130 to 10 atmospheres.[28]

At the beginning of the twentieth century, the inhaled anesthetics in standard clinical practice were ether, chloroform and nitrous oxide, while ethyl chloride and ethylene, introduced during the second half of the nineteenth century, were less popular.[29] For this reason, the new anesthesia devices in continual development were based on the properties of these three inhalation anesthetics. In 1901 Hewitt introduced his ether inhaler, which was a modification of Clover's earlier device (Fig. 8). The main change was to increase the diameter of the central breathing tube, which reduced the discomfort of the first respiratory efforts, while the patient was still conscious, and reduced the risk of rales, cyanosis and respiratory distress, which still affected anesthetized patients quite frequently. With this new device the tank did not rotate on the central pillar, but remained fixed; instead, the central tube, which was divided into two parts, could be rotated inside the tank, a procedure that made it possible to add ether to the tank without having to remove the inhaler from the patient's face.[30]

Figure 8 Hewitt's modification of Clover's portable ether inhaler (ca. 1901). Public Domain. Credit: Science Museum, London. CC BY.

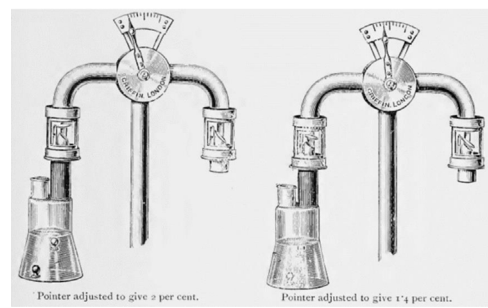

Figure 9 Harcourt Chloroform inhaler. Dudley W. Buxton (London: John J. Griffin, 1904). Public Domain. Credit Wellcome Collection. CC BY.

Another groundbreaking anesthetic machine, which appeared in Germany at the beginning of the twentieth century, was Roth-Dräger's oxygen and chloroform apparatus, that, despite its name, facilitated the joint administration of ether and chloroform. The first model of this device was presented by the surgeon Otto Roth in Berlin at the 31st Annual German Congress of Surgeons in 1902. This machine was one of the first to have a continuous supply of oxygen and allowed the controlled, reliable administration of a mixture of oxygen and anesthetic gases, propelled by mechanical means.[31,32]

In the United Kingdom, important advances in the delivery of chloroform were obtained with the devices proposed by Hartcourt and by Waller in 1903, and with the Levy inhaler in 1904. In 1901, the British Medical Association appointed a committee to investigate the mortality of chloroform and chose the chemist Vernon Harcourt to pilot this project. Harcourt built an apparatus (Fig. 9), described in 1903 in the *British Medical Journal*, designed to deliver no more than

Figure 10 Ombrédanne's apparatus. Image courtesy of the Museum of the History of Medicine and Science Institute López Piñero, Universitat de València-CSIC, Spain. Reproduced with permission.

2% chloroform in air, and with the capacity to compensate for a decrease in the concentration of the solution caused by changes in temperature.[33] Another pioneer, August Waller also considered that chloroform accidents were more likely to be caused by an overdose than to the idiosyncrasy initially attributed to the drug, and focused on laboratory studies to determine dangerous, fatal and minimum effective doses of the anesthetic. On the basis of his findings, he manufactured an anesthesia device that regulated the proportion of chloroform vapor supplied on a balance integrated within the device, which he termed the Waller Chloroform Balance.[34]

In 1904, in a further refinement to regulate the concentration of chloroform in the gas mixture, A.G. Levy developed an inhaler that allowed the operator to produce a maximum concentration of 3.5% of chloroform in inspired air. Levy's main contribution was to introduce a compensator preventing the interference of respiratory effort with the concentration of chloroform, as the respiratory pump acted as the driving force for the device. Before any deep breaths were taken, the compensator was activated manually to reduce the concentration of chloroform, thus avoiding an overdose.[35]

Finally, to end this section on complex inhalers, we must discuss the Ombredanne device of 1908 (Fig. 10),[36] another modification of Clover's inhaler. Louis Ombredanne, a Parisian surgeon, considered chloroform a very dangerous agent, and so he worked mainly with ether. However, he was critical of the apparatuses available for this purpose; although he was convinced that the efficiency of the ether was determined by the inhalation of its vapors in an enclosed space, he favored the intermittent admission of fresh air in order to avoid the supply of mixtures of hypoxic gases. Accordingly, he designed a new device that was fitted with a control to regulate the amount of ether vapor inspired, the fraction of exhaled air that the patient again inhaled, and the amount of new air that was added following each inspiration

Gas machines (1906-1930s)

Technological progress also led to the development of gas machines for use with nitrous oxide. These devices incorporated various components originally designed for other applications, but which greatly improved the performance and safety of the anesthetic machine. In Germany, in 1906, Franz Kuhn designed a closed circuit anesthetic machine with two canisters of soda lime to absorb carbon dioxide and valves to direct the flow of the gas. This machine, manufactured by the Dräger company, became known as the Kuhn-Dräger anesthetic machine and allowed positive pressure ventilation to be applied. However, the development of this machine was limited by fears about possible interaction between the chloroform and the soda lime.[37]

In 1908, Karl Küppers invented and patented the gas flow rotameter, which allowed physicians to regulate gases more precisely. In 1910, Maximiliam Neu designed an apparatus to supply nitrous oxide and oxygen, fitted with a rotameter to measure the flow of each gas (Fig. 11). However, the high cost of this anesthetic machine limited its development.[38]

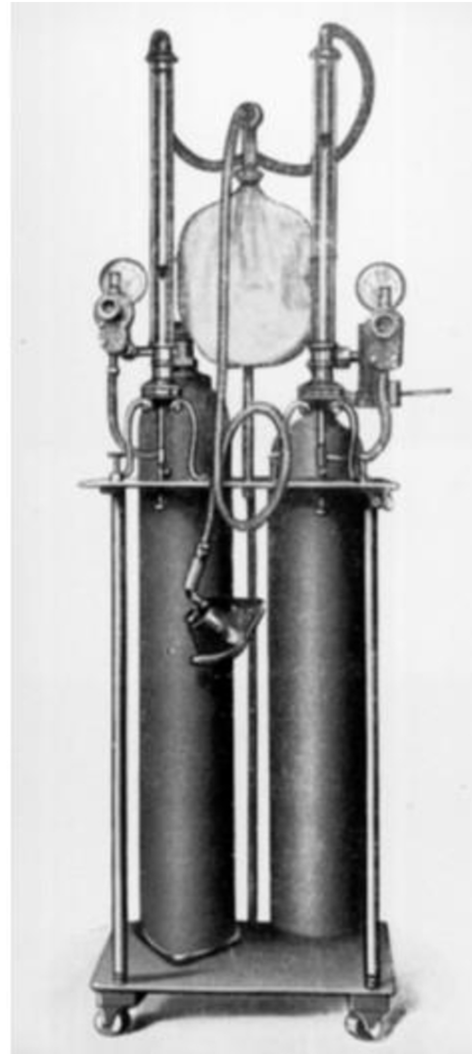

Figure 11 Neuś apparatus. Reprinted from *Best Practice & Research Clinical Anaesthesiology*, Vol 15 (3). M. Goerig, J. Schulte am Esch, History of nitrous oxide − with special reference to its early use in Germany, 331−338. Copyright (2001) with permission from Elsevier.

Figure 12 McKesson's apparatus, connected to cylinders of oxygen and nitrous oxide, which were used when the small gas tanks of the apparatus were exhausted. Public domain image. Courtesy of HathiTrust. Available at: https://babel.hathitrust.org/cgi/ptid=hvd.32044103003448&view=1up&seq=483.

In the United States, Elmer McKesson introduced a new concept for the provision of gas flow on demand during anesthesia and in 1910 he presented an intermittent flow device for the administration of anesthetic gases (Fig. 12). This was the first anesthetic machine to have an automatic cutoff regulated by the patient's breathing. With this device, the air current flowed only while the patient inhaled, and stopped when the patient exhaled, which produced important savings in anesthetic and medicinal gases. The machine was able to administer nitrous oxide, oxygen and ether, either alone or in combination.[39]

In Boston, two years later, in 1912, Cotton and Boothby developed an anesthetic machine that provided an uninterrupted flow of anesthetic gases and oxygen. In addition, a new method to visually measure the gas flow was incorporated. This method, termed the ''bubble bottle'', consisted of passing each gas separately through the water in a glass mixing chamber (and so they were also known as wet or water flow meters). The bubble rate of gases through the water was used to estimate the flow and proportion of each gas.[40,41] The Cotton & Boothby apparatus was subsequently used as a prototype for the manufacture of other anesthetic machines, such as the one presented by Crile and Teter at the 27th International Congress of Medicine, held in London in 1912. That meeting was attended by James Tayloe Gwathmey, the first president of the American Society of Anesthesiologists, and Dr. H. Edmund G. Boyle, among others, who later manufactured other anesthesia devices modifying and refining Cotton & Boothby's initial model.[42]

Gwathmey presented his anesthetic machine in Minneapolis in 1912 (Fig. 13). This device, which incorporated Cotton & Boothby's water flow meters and was manufactured by the Foregger company from 1914, allowed oxygen, nitrous oxide and ether to be administered, either singly or in combination through a stopcock. In addition, it regulated the proportion of anesthetic gases inhaled and was fitted with a lamp to heat the gases.[42–44]

Figure 13 Gwathmey-Woolsey nitrous oxide-oxygen apparatus with cylinders attached. O, regulating valve for oxygen; O_2, oxygen tank; N_2O, nitrous-oxide tank. Observe bubble bottle. Original image from Gwathmey JT. Anesthesia. New York: Appleton; 1914.

Shortly afterwards, in 1915, in St. Louis (USA), D.E. Jackson built an anesthetic machine which incorporated a closed circuit to reuse the exhaled gas and thereby reduce the costs of anesthesia. Moreover, it incorporated a carbon dioxide absorber, consisting of a solution of sodium hydrate and calcium hydrate through which the exhaled gases were passed. The machine could operate with nitrous oxide, ethyl chloride, ether, chloroform or ethyl bromide, among other anesthetic gases, in addition to oxygen, and also included a small electric motor that acted as an air pump.[45]

The growing acceptance of gas machines and continual developments in materials facilitating airway control led to the appearance of anesthesia based on endotracheal insufflation. In England, in 1916, Shipway manufactured a device enabling the insufflation of ''warm anesthetic vapors'' and highlighted the advantages of this form of administration in an article published in *The Lancet*.[46]

A year later, in 1917, Boyle developed his anesthetic machine from Gwathmey's basic model and presented it in London, at the Royal Society of Medicine, in 1918. The original design was composed of a wooden structure in the form of a box, which acted as a frame, with two transverse bars from which hung the cylinders of compressed gas (two of oxygen and two of nitrous oxide), an ether vaporizer and a water flow meter (the bubble bottle from the Cotton & Boothby apparatus). In addition, the machine had a manometer to measure the pressure in the cylinders, sensitive pressure-reducing valves and an alcohol lamp (to prevent the nitrous oxide from freezing and thus obstructing the cylinder). Boyle's anesthesia device, originally manufactured by Coxeter & Sons, and subsequently acquired by the British Oxygen Company, is considered the standard design

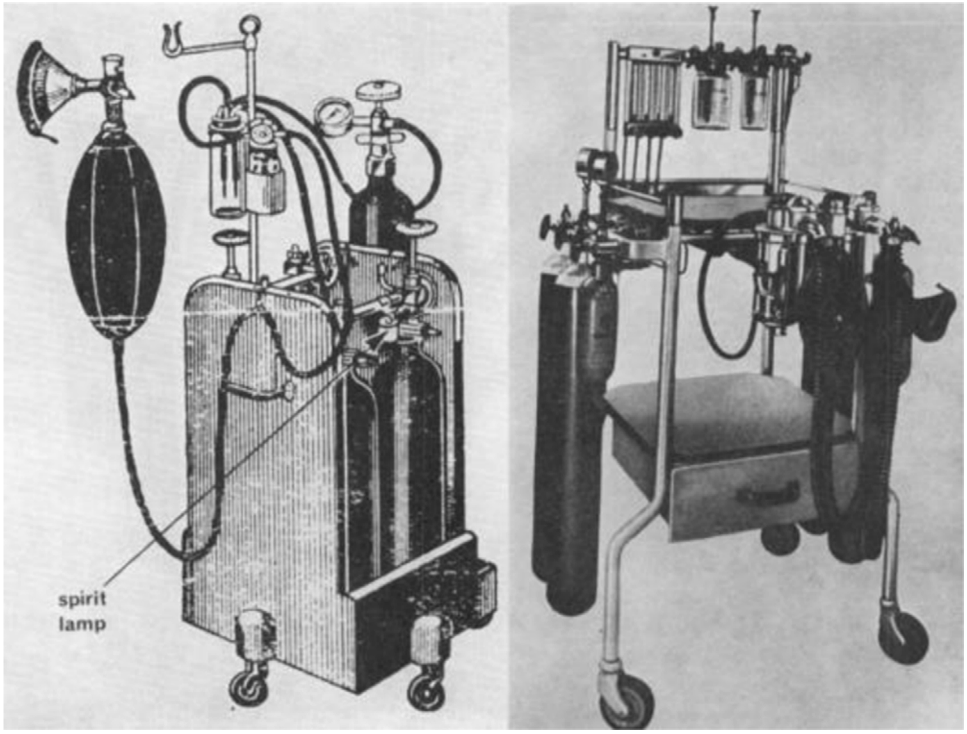

Figure 14 Boyleś Machine. Left: First model, with wooden frame, 1917. Right: 1958 model, with metal structure. Gas cylinders and pressure regulators are fixed to the frame of the table. In the upper part is the block of rotamers and vaporisers. Reproduced from Watt OM. The evolution of the Boyle apparatus, 1917–67. *Anaesthesia* 1968, with permission of Wiley & Sons.

Table 1 Evolution of the Boyle apparatus.

1920	Addition of a chloroform vaporiser
1921–1924	Incorporation of the Waters carbon dioxide absorption system
1926	Introduction of bypass controls to regulate the quantity of ether/chloroform
1927	Addition of a carbon dioxide flow meter
1930	Inclusion of a plunger device in the vaporiser
1931–1933	Substitution of water flow meters by dry flow meters
1937	Replacement of dry flow meters with flowmeters
1941	Incorporation of the C̈oxeter-Mushin Mark Ičircle absorber unit in Boyle's EMS model.
1952	Incorporation of non-interchangeable plugs in the gas connections.
1958	Incorporation of the Bodok seal in gas connections.[46,47]

for the physical composition of anesthesia stations today, although it has undergone numerous modifications since its first appearance (Fig. 14), as technological advances have been made[47,48] (Table 1).

A contemporary of the first version of Boyle's apparatus was the anesthetic machine proposed by the English barge commander Geoffrey Marshall, who in 1917 presented the Coxeter company with his own design for a sequential machine (inspired by Gwathmey's device) supplying nitrous oxide, oxygen and ether. The Coxeter company decided to manufacture the machine, and it became the standard anesthesia device of the Royal Army Medical Corps during the final stages of the First World War. However, Marshall did not publish his invention, and Boyle, who had attended the presentation of Marshall's machine, made some slight modifications, and presented it as his own device.[49]

In 1921, following the path suggested by Shipway, Magill introduced his first device for the tracheal insufflation of ether in hot air, a portable design that was very well received by anesthetists, who habitually worked on an itinerant basis. These initial designs received successive modifications between 1923 and 1932, enabling the joint administration of nitrous oxide and oxygen, and the incorporation of gas flow meters.[50,51]

In 1924, Ralph Waters introduced the use of granules for the absorption of carbon dioxide.[52] Based on the closed circuit proposed by Jackson in 1915, Brian C. Sword designed an anesthetic machine in 1930, which incorporated the first closed-circle circuit with carbon dioxide absorption through the Waters granules, which were composed of 50% calcium oxide and 50% sodium hydroxide. These granules were packed into cannisters and also acted as a dehydrating agent for exhaled gases.[53]

Modern vaporizers (1937-1952)

In the development of vaporizers, two moments in the twentieth century are especially significant. During Macintosh's first trip to Spain, in 1937, the deplorable state of anesthesia observed led him to design a portable ether inhaler that could be used in unfavourable circumstances. After contact-

Figure 15 Oxford Vaporiser. Image courtesy of the Geoffrey Kaye Anesthesia History Museum, Melbourne, Australia. Registration number 4724. Reproduced with permission.

ing Epstein, a physicist from Berlin, and other specialists in chemistry and physiology, he designed what became known as the Oxford vaporizer (Fig. 15). This device maintained the ether at a constant, high temperature, thus providing a continuous, high concentration of ether vapor, enabling the operator to supply a given, predetermined concentration of anesthetic gas, according to a scale marked on the machine. The Oxford vaporizer had three concentric chambers. The innermost one was filled with 400 cc of hot water. The middle one was hermetically closed and contained 1300 g of hydrated calcium chloride crystals. Finally, the outermost one was filled with ether. This arrangement maintained the ether at a constant temperature, and so the vapor pressure within the chamber also remained constant. In addition, the vaporizer was fitted with a connection enabling the administration of oxygen.[54,55]

Another major advance was achieved in 1952, when Lucien Morris introduced a new vaporizer for the administration of liquid anesthetic agents. Until then, the vaporizers available had been made of glass, and diverted part of the gas flow onto the liquid to be vaporised, in order to regulate the final concentration. However, this method only provided a coarse degree of adjustment. Morris replaced the glass container bottle, which tended to cool the anesthetic agent, with a copper container that retained the heat much better. In addition, he made changes to the circuit design and in the vaporisation area to obtain known, constant volumes of saturated vapor, thus achieving a precise vaporisation of the anesthetic gases to be inhaled.[56]

The Morris vaporizer became known as the ''Copper Kettle'', and was first manufactured by the Foregger company in the United States (Fig. 16). Copies of the design subsequently appeared in the United Kingdom, Japan, and South America, with certain modifications, and it became the vaporizer of choice for the administration of halothane.[57]

After the appearance of halogenated inhalational anesthetics in 1956, further designs of vaporizers were developed, including the Fluotec (Cyprane Ltd.) and the Vapor (Drägerwerk),[58] most of which were clearly influenced

Figure 16 Foregger Copper Kettle. Image courtesy of the Harry Daly Museum (Australian Society of Anaesthetists).

by the Copper Kettle, and their development has continued to the present day.

Integration of the ventilator (1930s-1960s)

According to Wilkinson, mechanical ventilators were introduced into anesthetic practice in the early 1950s and quickly became standard components of anesthetic machines, within equipment such as the Blease Pulmoflator, the Engström apparatus, the Cape machine and the Barnet machine.[59]

This evolution was marked by various significant developments. Intraoperative artificial ventilation was first introduced in thoracic surgery, an area of medicine that presents a singular problem: when the pleural space is opened, this provokes a pneumothorax, the magnitude of which is largely related to the size of the thoracotomy. For many years, pneumothorax was the major problem facing thoracic surgeons, since this condition could lead to the collapse of the exposed lung, paradoxical breathing and hemodynamic problems.[60]

Two contrasting approaches were taken to this problem. On the one hand, since 1828, when Leroy discovered that positive pressure ventilation produced barotraumatism and pneumothorax,[61] there had been great skepticism within the scientific community about this type of ventilation. In consequence, the field of mechanical ventilation was dominated by negative pressure ventilation systems, which all operated in a similar fashion: the patient's body was placed inside a more or less airtight chamber, with the head protruding. A negative pressure was then applied within this chamber, causing the thorax to expand. When the atmospheric pressure was subsequently restored, exhalation took place.[62]

In 1904, in line with this view, Ferdinand Sauerbruch, a German surgeon, built a negative pressure chamber, within which thoracic cavity surgery could be performed without provoking the collapse of the lung. After achieving good results with this device, Sauerbruch travelled through the USA and several European countries to promote his differential pressure chamber.[63]

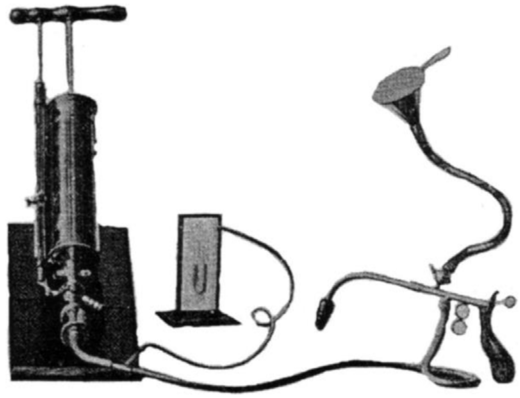

Figure 17 The Matas-Smythe modified Fell-OĎwyer apparatus for artificial ventilation. Original image from reference.[70]

However, other pioneers in this field took a very different approach. In 1896, two French surgeons, Tuffier and Hallion, proposed a means of overcoming this problem via the insufflation of air through the larynx or trachea to achieve distension of the lung, after successful experiments in this respect with dogs under positive pressure ventilation and laryngotracheal intubation.[64] The promising results obtained with these animal experiments encouraged Tuffier and Hallion to use artificial intraoperative ventilation with human patients,[65] a feat enabled by their mastery of respiratory physiology and the effective regulation of inhalatory anesthesia during artificial ventilation.[66]

A year later, Milton's ''Mediastinal Surgery'' was published in *The Lancet*. In this paper, the author referred to the thoracic cavity as ''terra incognita'' for the surgeon, and highlighted the need for ventilation with positive pressure when operating in this area.[67]

The potential benefits of artificial ventilation in thoracic surgery were also apparent to Rudolph Matas, a New Orleans surgeon of Spanish origin. Matas was convinced that, through the use of artificial respiration, intrathoracic surgery could be successfully performed.[68,69] Accordingly, Matas collaborated in 1902 with John Smythe in the design of a new device based on the Fell-O'Dwyer apparatus (Fig. 17), consisting of a graduated cylinder for the precise administration of the desired volume of air (up to 1500 mL), a mercury manometer to measure intrapulmonary pressure and a modified Fell-O'Dwyer cannula fitted with a port to facilitate the administration of oxygen or chloroform during artificial respiration.[70]

As observed above, the Kuhn-Dräger anesthetic machine, which provided positive pressure ventilation by means of a bellows, was manufactured in Germany in 1906. However, worries about the possible interaction of the soda lime with chloroform, together with the hostility towards positive pressure ventilation displayed by Sauerbruch, an influential figure of the time, limited its development.[31]

Despite the widespread objection to the use of positive pressure ventilation outside the operating room, designers sought to overcome the problem of pneumothorax in thoracic surgery by creating devices that integrated a manual ventilator for the application of positive pressure, associated with anesthetic vaporizers or nitrous oxide bottles. Such devices included the Brat & Schmieden apparatus (1908) (Fig. 18), the Tiegel apparatuses (1908 and 1909) and the Lotsch positive pressure apparatus (1910)[60] (Fig. 19 and 20).

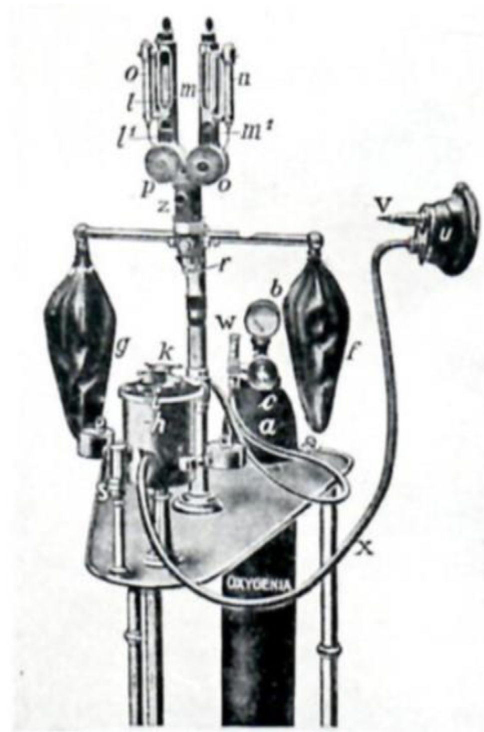

Figure 18 Brat & Schmieden's apparatus (1908). Reproduced from reference[60], with permission of Wiley & Sons.

New York doctors Nathan W. Green and Henry H. Janeway were working along the same lines, and in 1910, they published a paper reporting their experiences with mechanical ventilation during thoracic surgery on animals. In particular, a dog that had been treated with curare and then underwent thoracic surgery was kept alive for four hours with the intermittent application of positive pressure ventilation. These authors also observed that the conditions for thoracic surgery were more favorable when it was performed under artificial ventilation.[71] In this area, too, Janeway and Green described an apparatus for the application of mechanical ventilation. This was an adaptation of Brauer's invention for the application of positive pressure to the airway during thoracic surgery. The greater sophistication of this machine, and the synchronization provided, enabled patients to receive ventilation independently of their own breathing.[72]

In 1916, Giertz demonstrated, through animal experimentation, that artificial ventilation by rhythmic insufflation was preferable to assisted respiration with constant differential pressure as proposed by Sauerbruch. From these observations, the Swedish surgeon Frenckner developed the ''Spiropulsator'' (Fig. 21), a mechanical ventilator that administered the mixture of anesthetics during artificial ventilation. In 1933, Frenckner, working with two Swedes, the engineer Anderson and the surgeon Crafoord, designed an anesthesia device that provided intermittent positive ventilation. This new machine, known as the ''Frenckner-Crafoord-Anderson'' apparatus, was a combination of the Spiropulsator and an anesthesia device manufactured by the

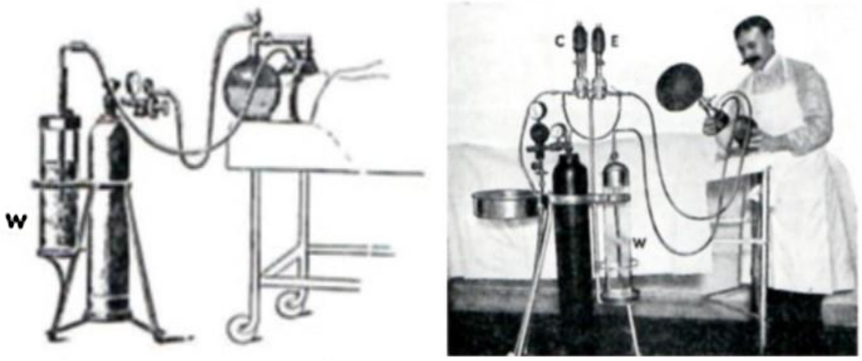

Figure 19 Tiegel's apparatuses. Left: 1908 version. Right:1909 version. Reproduced from reference[60], with permission of Wiley & Sons.

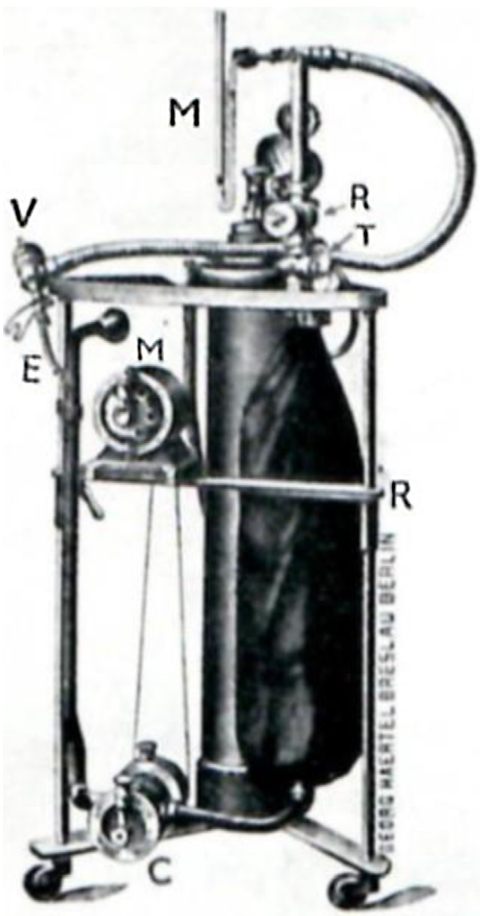

Figure 20 The Lotsch positive pressure apparatus (1910). Reproduced from reference[60], with permission of Wiley & Sons.

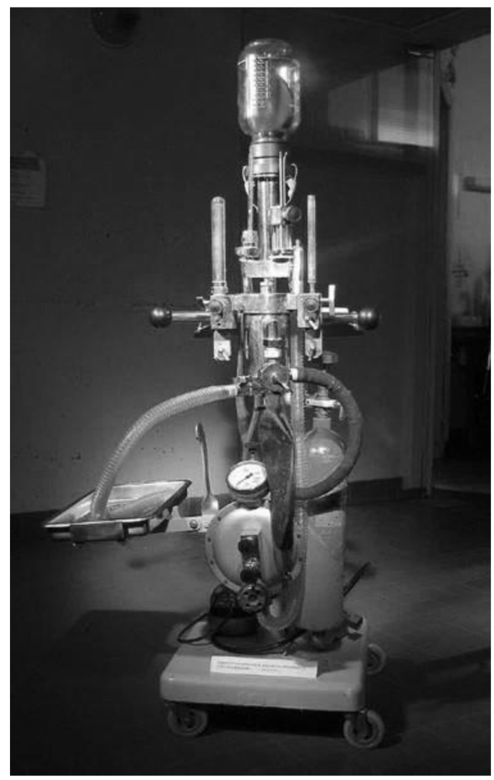

Figure 21 Frenckner Spiropulsator. Image courtesy of the Anesthesia Museum of the Besançon Hospital, France. Reproduced with permission.

AGA company, and was used by Crafoord in the anesthesia of several hundred patients undergoing major thoracic surgery.[73] The Frenckner-Crafoord-Anderson device can be considered the first hybrid anesthesia apparatus in which an electric ventilator was an integral component.

Despite the good results obtained with positive pressure intraoperative ventilation, in 1937 Sauerbruch still considered this technique dangerous and unnecessary.[74]

Trier Moerch, a Danish doctor who was a member of the resistance during the German occupation in World War II, received permission to study anesthesiology at the Karolinska Institute, Stockholm, in 1943. During his stay in Sweden, he learned to use the Spiropulsator and once back in his country, he designed and produced a respirator, despite the shortage of materials available due to the wartime blockade.[75] Moerch combined his respirator with McKesson-Nargraf's anesthetic machine to produce a new hybrid device (Fig. 22), consisting of an electrically operated piston pump, which was inserted into a closed circuit and replaced the ventilation bag.[73]

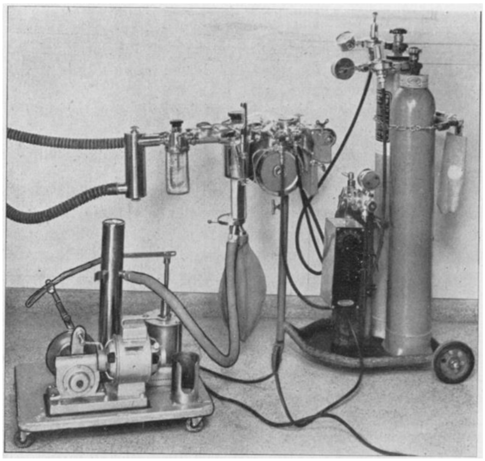

Figure 22 McKessonś machine with Trier Moerch's Respirator. Figure from Moerch ET. Controlled Respiration by Means of Special Automatic Machines as Used in Sweden and Denmark. Anaesthesia 1948, with permission of Wiley and Sons.

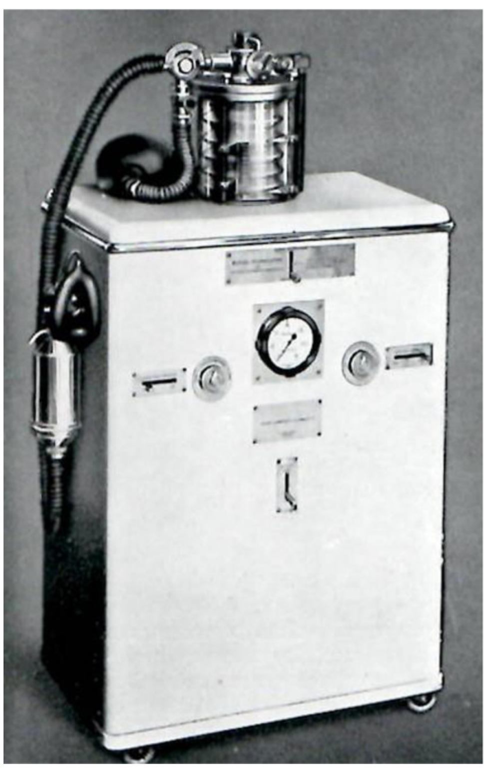

Figure 23 Blease Pulmoflator. Reprinted from *British Journal of Anaesthesia*, Vol 26 (2). Mushin WW, Rendell-Baker L. Modern Automatic Respirators, 131–47, Copyright (1954), with permission from Elsevier.

In 1945, in Liverpool (UK), John H. Blease designed an intermittent positive pressure ventilator. After the war, in 1947, an improved version, the Pulmoflator, was produced (Fig. 23). This was the first positive pressure ventilator to be made in Britain, and successive improvements and sophistications were patented. In 1953, Blease incorporated the Pulmoflator P.1 within an anesthetic machine, terming the device ''The combined Pulmoflator'', P.2. This new version included rotameters for gases, including cyclopropane, together with gas cylinders, apparatus for blood pressure measurement, an aspirator, bronchoscope accessories and an instrument tray.[76,77]

Figure 24 Dräger Romulus (1952). Image courtesy of Drägerwerk AG & Co. KGaA, Lubeck. All rights reserved. Reproduced with permission.

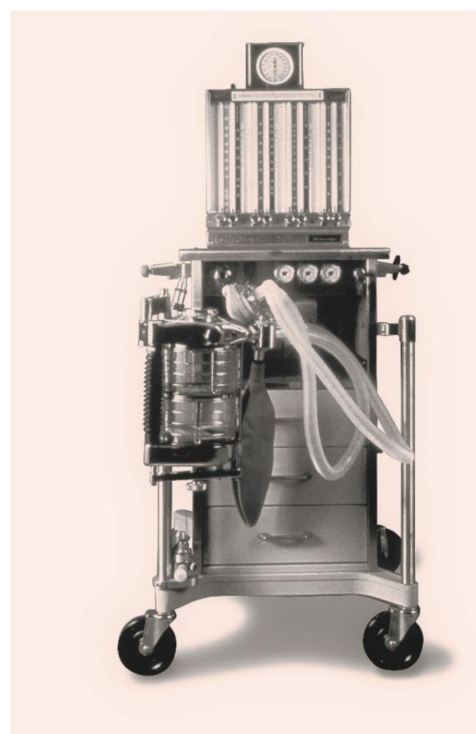

Figure 25 Ohio DM 5000 anesthesia machine. Public Domain. Available at: https://www.flickr.com/photos/gehealthcare/5101978942/in/album-72157625084928691/.

In parallel with the development of positive pressure ventilators, the widespread adoption of intermittent positive pressure ventilation in surgical anesthetic practice was favoured during the late 1940s and early 1950s by two important events: the introduction of curare into clinical

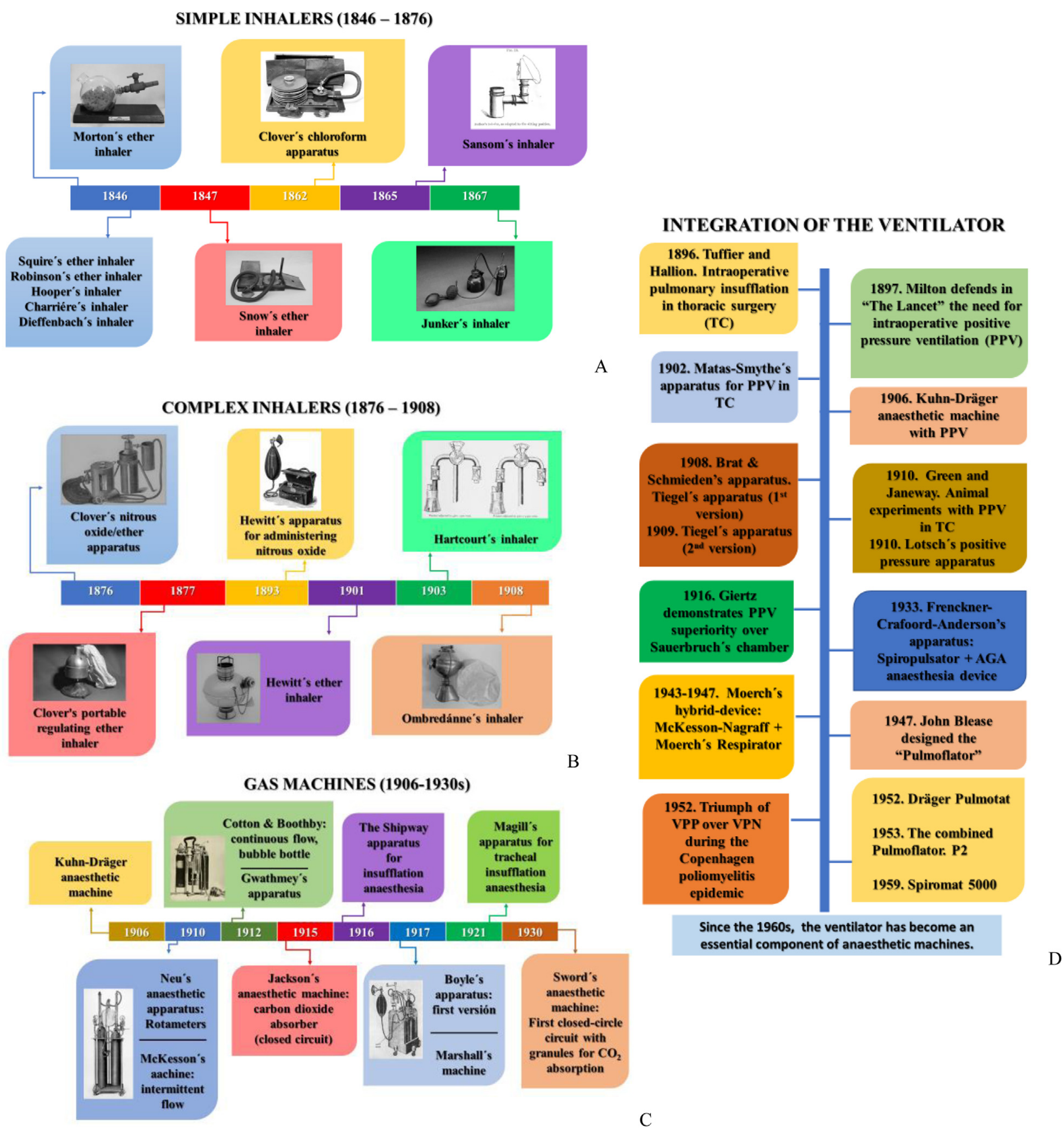

Figure 26 Panel A, Time line for simple inhalers; Panel B, Time line for complex inhalers; Panel C, Time line for gas machines; Panel D, Time line for ''integration of the ventilator''.

anesthetic practice,[78] and the triumph of positive pressure ventilation over negative pressure ventilation in 1952, during the Copenhagen poliomyelitis epidemic.[79]

These events boosted the acceptance of the ventilator in anesthetic machines. Thus, during the 1950s, in addition to the ventilator-equipped anesthesia apparatus described by Wilkinson, the Dräger company produced the ''Dräger Pulmomat'' in 1952. This was a new type of ventilator designed as an additional unit to be connected to any Dräger anesthetic machine with a circle system. The Dräger Romulus model of 1952 (Fig. 24), was one of the anesthetic machines in which the Pulmomat was incorporated. Later, in 1959, the Spiromat 5000 anesthetic machine was designed as a combination of the Spiromat 4900 long-term ventilator and the Romulus anesthetic machine.[80]

From the 1960s, Ohio Medical Products began incorporating ventilators into their anesthesia equipment, in the 4000 series and in the DM 5000 model[81] (Fig. 25). Since then, the ventilator has become an essential component of anesthetic machines.

Conclusions

In just over a century, devices for the administration of anesthetic gases have evolved from simple inhalers to sophisticated anesthetic machines, spurred by the ever-greater precision achieved in the mixtures inhaled. Other relevant factors in this progress were financial considerations and concerns for patient safety. Initially, anesthetists played a leading role in the design and manufacture of new devices, but they were later supplanted by large companies and became mere users of the technology. Moreover, the historical development of inhalational anesthetic agents influenced the evolution of the anesthetic machine, since many devices were designed according to the physical and chemical properties of specific agents. Finally, the integration of the ventilator into the anesthetic machine was a crucial development, fundamentally changing the anesthetists' functions involved. Mechanical ventilation freed the operator's hands, enabling other intraoperative tasks to be undertaken, an advance in which the needs and conditions of thoracic surgery were of decisive importance.

Figure 26 (panels A to D) shows the timelines for simple inhalators, complex inhalators, gas machine, and the integration of the ventilator in the anesthesia machine. In these, we can see a summary of the major advances in the development of these devices.

Conflicts of interest

The authors declare no conflicts of interest.

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