DEVELOPMENT OF ANAESTHETIC MACHINES

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'It is abundantly clear that, during the past few years, there has been a remarkable resurgence of interest in all aspects of the history of anaesthesia, and not least in that of anaesthetic apparatus. Not only academic departments of anaesthesia, but also smaller general hospitals are now admitting to some form of collection of historical anaesthetic apparatus which has been garnered by devotees, often over many years, rescuing important items from the over-enthusiastic clearance of theatre store-rooms and cupboards. One of the most notable collections in Britain is the Charles King collection owned by the Association of Anaesthetists of Great Britain and Ireland. This collection was assembled patiently over his lifetime by the instrument maker A. Charles King and has since been augmented by items from all parts of the world. It was described in detail by Thomas (1975). To anyone familiar with this work, the sheer impossibility of attempting to describe the development of the anaesthetic machine in a single article must be only too apparent. However, the writers feel that there are certain pieces of apparatus or innovative developments which stand out from the historical scene as milestones in the continuing evolution of our specialty, and which can reasonably be regarded as turning points in the equipment story. Our purpose is to highlight these and not to make any attempt to describe in detail the history of particular pieces of equipment. Many others have already given clear and detailed accounts of such history (Miller, 1941; Waters, 1946; Duncum, 1947; Jackson, 1955; Sykes, 1960/61, 1982; Rendell-Baker, 1963, 1980; Thomas, 1975; Wilkinson, 1984).

It is probably true to say that the efforts of those developing anaesthetic apparatus have been directed towards increasing safety, improving accuracy and, particularly recently, studying the ergonomic aspects of machine design and adding to sophistication. While designers would, no doubt, claim that in every instance the achievement of the second and third aims has contributed inevitably to the achievement of the first, there are many who consider the reverse to be true, since increasing complexity often engenders an increase in the opportunities for failure.

The claims of Crawford Long for primacy in the introduction of ether are now clearly recognized (Sykes, 1982); however, since he used the corner of a towel (Young, 1897), it is not unreasonable to regard Morton's draw-over apparatus as the forerunner of all (fig. 1). Simple as it was, it nevertheless incorporated some design features which have persisted until today or which could well be emulated. The ease with which it could be replaced is emphasized in the classical, albeit unproven, story of Morton's having dropped the device and broken it on his way to the public demonstration at the Massachusetts General Hospital on October 16, 1846. Even in this apparatus, the most basic principle of vaporization was appreciated and incorporated. Bigelow (1846) described "sponges to enlarge the evaporating surface" and there was little resistance to respiration with the wide-bore inspiratory tube. The evidence cited by Thomas (1975) also makes clear how rapidly improvements could be made, inasmuch as the model used on October 16 had no valves, whilst that used in the second operation on October 17 and described in Bigelow's paper did incorporate valves in the brass mouthpiece. A multiplicity of vaporizers was rapidly produced and the records of the Westminster Medical Society (later the Medical Society of London) show that there were frequent meetings at which these were demonstrated by their proud inventors.

True efficiency and accuracy in these early devices were not deemed important. Surgeons,
used to operating on conscious, restrained patients were, by today's standards, unbelievably rapid in their work. Patients needed to be anaesthetized for only a short period to permit surgery to be completed. With the advent of effective anaesthesia, surgeons became more adventurous in the type of operation they were willing to undertake and also began to take greater care in minimizing the trauma suffered by their patients. Operations began to take longer and longer and more efficient apparatus was needed to cope with this.

Snow's ether inhaler (fig. 2) was described in his book on ether (1847) and demonstrates the thought and knowledge which he applied. He appreciated, even in those early days, the need for wide-bore tubing, adequate exposure of the ether area, and warming of the vaporizing chamber. Moreover, he specified most carefully the height of the screw-on air inlet tube required to combine minimum resistance to the ingress of air with effective "prevention of a trifling loss of ether which would arise from evaporation of it into the apartment".

Snow also developed, in 1848, a chloroform inhaler (Duncum, 1947), but his famous administration of chloroform to Queen Victoria on April 7, 1853 was described in his diary "I commenced to give a little chloroform with each pain by pouring about 15 minims by measure on a folded handkerchief". On April 14, 1857 at the birth of Princess Beatrice, he "poured about 10 minims of chloroform on a handkerchief folded in a conical shape for each pain". It may be noted that he also recorded that "Prince Albert had previously administered a very little chloroform on a handkerchief" (Snow, 1853, 1857). This, however, was not full surgical anaesthesia, and Snow was utilizing the analgesic phase of chloroform inhalation to provide obstetric analgesia.

In the following years there were two main lines
of development. One was concerned with regulating the amount of vapour inhaled and the other was the utilization of nitrous oxide and oxygen as these became available stored in cylinders. In 1862 Clover showed his chloroform apparatus (fig. 3) at the International Exhibition in London. This apparatus enabled the administration of a known concentration of chloroform vapour in air. It was made to a specification drawn up by Clover himself—a specification which was detailed in every respect as to the construction, the nature of the layers of the bag, its volume and the stroke volume of the bellows used to inflate the bag. Unfortunately, one manufacturer produced a Clover bag which did not match this specification, in that the capacity of the main reservoir bag was less than that suggested by Clover. In fact it held not 11 000 but 8 400 cubic inches. It was also found subsequently that prolonged storage had made the bellows stiff and they did not deliver the supposed 1000 cubic inches per stroke. This meant that the concentration of chloroform vapour within the reservoir bag was considerably greater than was intended and this resulted, on May 15, 1873, in the death of one Thomas Breton, an inmate of Broadmoor Asylum for the criminally insane. Subsequently, Clover himself examined the bag with Mr Coxeter and the defects they found were reported immediately to the Lancet (Orange, 1873). Perhaps it was this event which can be regarded as the first appreciation of the necessity for accuracy and conformation with standard specifications which has become so much a part of the anaesthetic equipment industry today.

In 1877, Clover described his portable regulating ether inhaler (fig. 4). Rotation of the control determined the proportion of each breath which was diverted into the ether chamber. This was the first attempt to quantify a vaporizer and, although the apparatus was not calibrated in percentages, it was a considerable step forward. It may also be noted that the diameter of the face-mask fitting was 22 mm—a standard which is accepted internationally today!

The Clover type of ether inhaler remained popular in the U.K. for many years. Hewitt improved on Clover's ether inhaler with his wide-bore version in 1901; this reduced the resistance to respiration and allowed easier manipulation of the control, and the face-mask was screwed to the reservoir—a forerunner of the anti-disconnect devices which are gaining increasing favour today. It was as late as 1908 that Ombredanne published the paper on his ether inhaler (fig. 5). He paid particular attention to respiratory resistances and to the incorporation of a stepped air inlet. This vaporizer became more widely accepted on the European mainland than either the Clover or Hewitt models.

Although nitrous oxide was the agent used by Horace Wells in 1845, its widespread use was limited considerably by the need to maintain a
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Fig. 5. Ombrédanne's ether inhaler.

The entire story of nitrous oxide anaesthesia has been comprehensively reviewed by Smith (1982). In the period 1860–1870, a wide variety of designs of "gasometer" was marketed. The firms of Barth and Coxeter & Son were manufacturing nitrous oxide in 1868 and supplying it in iron bottles; in 1870 they succeeded in liquefying the gas. However, the compressed gas was not easy to control, although various ingenious devices such as Hele's Governor (Duncum, 1947) were introduced in the 1870s. Even so, in 1876 Clover was able to develop his nitrous oxide and ether apparatus (fig. 6). This was the first attempt to use a nitrous oxide–ether sequence. Perhaps of all historical apparatus, this particular device has failed to receive the recognition that it deserves. Anaesthesia was induced with nitrous oxide from the reservoir bag and maintained with ether drawn through the vaporizer. This greatly facilitated an otherwise prolonged ether-in-air induction and must have been more pleasant for the patient. Air was not admitted until cyanosis or jactitation occurred. Clover himself, however, never liked this apparatus and preferred his portable regulating ether inhaler which rapidly became modified with the addition of a stopcock and bag to permit sequential anaesthesia.

In the 1880s, technology succeeded in storing pure oxygen, prepared by the newly developed Lind process, in steel cylinders at high pressure. Figure 7 shows a cylinder which bears a test stamp for the year 1885. It was a prerequisite for the utilization of compressed gases stored in this way that there should be a serviceable and efficient means of controlling both the flow and pressure of the gas released. The founders of Drägerwerk, Heinrich Dräger and his son Bernhard, became involved with compressed gas engineering while it

Fig. 6. Clover's nitrous oxide/ether apparatus.

Fig. 7. Oxygen bottle from 1885.
was still in its infancy. They were originally acting as agents for equipment used in connection with the compressed gas pressurization of beer barrels. Being unsatisfied with various apparatus from diverse origins and of considerable unreliability, they decided that their first step should be to develop an ‘‘excellent and efficient’’ pressure reducing valve. Heinrich Dräger described those already available as ‘‘very undiscriminating’’ and that ‘‘they were very often disappointed with performance’’. As a result of their thinking they developed a completely new construction. Since the manufacturers for whom they were agents declined to take up this new valve the Drägers set up in business on their own. From this Bierdruck Automat—a mechanism for the automatic control of carbon dioxide pressure in beer pumps—stemmed the effective control of compressed medical gases. This development was followed almost immediately by their production of an effective control valve for cylinders, and the combination of these two allowed an even flow of gas to be drawn from a high pressure cylinder with accuracy, regardless of whether the pressure in the cylinder was high or low. These two inventive engineers were also the first to introduce the injector to a variety of anaesthetic apparatus and ventilators. However, in Britain, anaesthetic reducing valves continued to be based on that developed originally by Beard (fig. 8) for the control of acetylene–oxygen mixtures for limelights.

In the 1890s Hewitt had also introduced, as part of a nitrous oxide and oxygen apparatus, his nitrous oxide and oxygen stop-cock, which allowed the administration of a mixture of nitrous oxide and oxygen (Hewitt, 1897). Hewitt pointed out that it was impossible to state with precision what percentage of oxygen would be delivered at any given setting. He also stressed the importance of equalizing the pressure in the oxygen and nitrous oxide reservoirs and produced a conjoined pair which shared a common septum—the forerunner of the pressure-equalizing devices which were to be so important in the development of the intermittent flow machines such as the McKesson and Walton.

No review of the development of anaesthetic apparatus can omit the work of Harcourt (1903). The place of his apparatus (fig. 9) was stressed by Wilkinson (1984). He wrote ‘‘one of the most popular of the chloroform vaporizers was that designed by Vernon Harcourt. This apparatus was
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Fig. 10. Roth-Dräger mixed anaesthesia apparatus.

said to deliver not more than 2% chloroform in air regardless of the respiratory volumes. It was calibrated as accurate over a specific temperature range and incorporated a form of thermometer in the vaporizing chamber. This consisted of two special beads which floated or sank depending on the temperature of the liquid chloroform; the glass bottle containing the liquid could be heated on some models by the use of a candle to achieve the correct working temperature—heating must have increased the levels of phosgene delivered considerably! However, the apparatus demonstrates many sophisticated design points that would be incorporated in later equipment notably its air bypass, temperature compensation, and compensation for the fall in chloroform levels by tapering the glass bottle in which it was held.”

In summary, therefore, just after the end of the 19th century a point had been reached at which it was possible to give relatively uncontrolled nitrous oxide and oxygen mixtures (the precise proportion of oxygen in which was not known for certain), together with a volatile agent.

In 1902 the Drägers produced their first anaesthetic apparatus in conjunction with Dr Roth of the Lubeck General Hospital (fig. 10). This incorporated an oxygen cylinder and reducing valve, the oxygen being used to operate two injectors which sucked ether or chloroform, or both, from separate bottles for evaporation, the number of drops being carefully regulated. However, what was still missing was an accurate control and means of measuring gas flow. Cotton and Boothby (1912) were the first to use the “bubble bottle” for visible gas measurements in anaesthesia. It was this development which lead to the apparatuses devised by Gwathmey, Marshall, Boyle and others. As Smith (1982) noted in his book, “Boothby and Cotton had made worthwhile advances in the design of apparatus. Knowledge of the amount of each gas being used was ‘obtained by passing the gases through water into a mixing chamber; the rate of the bubbling of the gas through the water gives a very accurate index of the percentages of the two gases as administered to the patient’”. Undoubtedly, this was a fundamental step which preceded by a very few years the development of the Gwathmey and Boyle apparatuses. Accurate though these flowmeters were compared with previous methods, they must have been very difficult to read. Relatively low gas flows produced considerable turbulence and made accurate readings difficult. They did, however, have the advantage of humidifying the inspired gases. Rendell-Baker (1963) pointed out that “Rotameters were first used in industry in Great Britain before the first world war and were also employed to measure gas flows by manufacturers of medical gases. Their use in anaesthesia was later explored by McCardie of Birmingham and Magill in London, but it was not until 1937 that Rotameters became available commercially for anaesthesia after their modification had again been suggested by Salt”. Rendell-Baker also noted that Neu in 1910 produced an experimental nitrous oxide-oxygen apparatus with Rotameters made by Deutsche Rotawerke of Aachen which were identical in principle with those of the present day. He suggested that their large size and high cost were the reasons for the lack of interest shown by the rest of the world, and that the fact that nitrous oxide was imported into Germany was a further factor retarding the development of this early and accurate method.

The contributions of Gwathmey to anaesthesia were monumental (Thomas, 1975). One of the first physicians in the United States to confine himself entirely to anaesthetic practice, he reported on 20000 successful cases of the use of rectal ether in midwifery, produced a comprehensive text book (Gwathmey, 1914), and was largely instrumental in the development of the American Society of Anesthesiologists. During the 1914–18 war he and Boyle of St Bartholomew’s Hospital in London...
renewed an earlier acquaintance. Gwathmey had introduced his apparatus in 1912 using the same type of flowmeter as Cotton and Boothby. No pressure reduction of the compressed gases was included, but stress was laid on warming the inspired gases, and the use of a “sliding cuff” inspiratory and expiratory valve which allowed regulation of degree of rebreathing. Marshall, also working in France during the war, developed an apparatus for giving gas, oxygen and ether with wet flowmeters. A prototype of his apparatus was produced by Coxeter and this became a standard model in the Royal Army Medical Corps. However, before Marshall had published an account of his apparatus (1920), Boyle had described his apparatus (1917, 1919), which was purely an English modification of Gwathmey’s design. Thus, as Thomas said, “the name of Boyle became forever associated with this type of anaesthetic apparatus”. As Hadfield (1950) said, “Boyle and his contemporaries played an important part in bridging the gap between earlier methods and those which were developed into the techniques of today”. The situation was summed up by Thomas “...Gwathmey and Marshall developed the use of nitrous oxide with oxygen and produced a new method of gauging the gas flows. This was the idea which was then taken up by Boyle”. The steady development of this type of apparatus from 1917 (fig. 11) to the present day is one of steady refinement. In his 1927 model, a flowmeter for carbon dioxide was included, the volatile controls were of the lever type and the familiar back-bar made its first appearance. The plunger of the vaporizer appeared in the 1930 model (fig. 12), and in the 1933 model Coxeter dry bobbin flowmeters were incorporated.

The early development of vaporizers has already been described under such headings as Clover, Harcourt and the Boyle apparatus. Over the past 20 years the steady development of a wide range of accurate temperature-compensated vaporizers such as the Fluotec, Dräger “Vapor”, and “Abingdon” suitable for use with low flows of fresh gas has taken place. The development of these vaporizers has been described by Wilkinson (1984).

Mention should be made of the development of closed breathing systems and carbon dioxide absorption. This is indelibly and inextricably linked with the name of Waters of Madison. However, the development of carbon dioxide absorption was originally undertaken to meet the requirements of the mining industry. On June 15, 1856, Schwann breathed from his newly-invented mine rescue apparatus, which incorporated an absorption chamber for caustic soda, for 1 h 45 min. Again, the Drägers played a key role in the development of subsequent apparatus and produ-
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In all too limited a space, an attempt has been made to outline in the barest detail the development of the modern anaesthetic apparatus. No mention has been made of such equipment as the open mask, the intermittent flow machine, the incorporation of lung ventilators in the apparatus, or the increasing inclusion of warning and monitoring devices. The situation is constantly changing. It may well be that by the time this article is read the appearance of a revolutionary "third generation" of anaesthetic machine may have been reported—one which applies a truly up-to-date refinement to, \textit{inter alia}, an aspect to which particular attention has been paid here: the increasing accuracy of delivered mixtures. There have been many changes in the development of anaesthetic apparatus since 1846. Essentially, however, little has changed since the 1930s when Boyle refined his original apparatus. Unfortunately, most equipment is now the province of the multi-national corporations who produce apparatus based on ISO requirements, published or in draft (Thompson, 1983), and not those of the anaesthetist. Most anaesthetists today lack the facilities, aptitude or time to manufacture their own equipment and are thus increasingly dependent on what is made for them. Instrument manufacturers have large sums of money invested in tooling and factories and are often unwilling to make major changes in design. It is surely time for a reappraisal of this situation. It is time also for the anaesthetist to begin influencing anaesthetic apparatus manufacturers again to ensure that the evolution of our specialty continues to keep pace with the developments in engineering and bio-mechanics that are taking place today.

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REFERENCES


