Chapter 2
Negative Pressure Noninvasive Ventilation (NPNIV): History, Rationale, and Application

Norma MT Braun

Dedication

This chapter is dedicated to Jack Haven Emerson (1906–1997), who designed the most effective, widely used noninvasive negative pressure ventilator, the iron lung, in the first half of the twentieth century, and to Dr. Dudley F. Rochester, my mentor, who did so much of the research to begin our understanding of the basis of their physiologic effectiveness, and to my patients who have taught me more than they can know.

Introduction

Man has recognized the vital role of breathing since antiquity, beginning with archeological findings depicting inhalation therapy using herbs, oils, and other substances since 6000 BC [1]. Man has taken the automaticity of breathing for granted, expecting its adequacy for all activities whether awake or asleep. Dickinson W. Richards, MD, Nobel Laureate, said in 1962: “Breathing is that essential physiologic function that is straddled between the conscious & the unconscious and subject to both” [2]. The understanding of the components of this critical physiologic function that starts at birth, and must be continuous and widely adaptable to support all levels of physical, metabolic, and functional needs, has evolved slowly over the millennia by many brilliant scientists from a combination of keen observation, imagination,

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R. C. Basner, S. Parthasarathy (eds.), *Nocturnal Non-Invasive Ventilation,*
DOI 10.1007/978-1-4899-7624-6_2

daring experimentation, trial and error, and necessity, while overcoming dogma, religious inhibitions and politics. It is this gradual chronologic process, still evolving, which guides what we do for patients today.

Breathing is an automatic, unconscious act until it is not sufficient—when symptoms of breathlessness and distress develop, or when life itself is threatened. All normal breathing is by negative pressure, accomplished by the development of negative intrathoracic, or below atmospheric pressure, when the inspiratory muscles contract, predominantly through diaphragmatic descent, distending the rib cage, thus allowing the pressure gradient from the higher atmospheric pressure to cause air to flow through open airways into the elastic lungs and chest wall. Simply relaxing these muscles allows for recoil of the lungs and chest wall to effect exhalation until higher workloads require the recruitment of additional muscles. It took hundreds of years to learn to recognize and understand this.

The slow and gradually accelerating evolution of knowledge regarding the vital connection of breathing to life and how its loss needed to be addressed was recognized as early as 3150 BC. To appreciate this process, it will be necessary to address its evolution from managing primarily respiratory emergencies with both "invasive" and "noninvasive" positive pressure ventilation (NIPPV) to the development and successful use of negative pressure noninvasive ventilation (NPNIV), enhanced by the polio epidemics, by ingenious designs, by better communications, by the availability of reliable power, by the necessary financial support, and from improved systems of care whose highlights will be chronologically described below.

The History of Ventilatory Failure and the Beginnings of Assisted Ventilation

An unknown philosopher stated "The lungs are the center of the universe and the seat of the soul [3]". The earliest reference for attempts to restore breathing was about 3150 BC when Egyptian physicians tried to save drowned victims by placing a reed in the throat and blowing into the lungs [4]. The Chinese in 2000 BC described *lien ch'i*, as a transfer of inspired air into the "soul" (life): mouth positive pressure. In the Old Testament book of Genesis 2:7, written between 1450 and 1410 B.C. by Moses, God is described "as breathing life into his dust created man by breathing into his nostrils" & thus "man became a living thing" and "when his breath was taken, he died & returned to dust." Further, it was written in 2 Kings 4: 34–35 that the Prophet Elisha "…went up…placed his mouth upon his mouth…and again…the child sneezed seven times…opened his eyes [5]."

There were long hiatuses in recorded history with sporadic descriptions on the essence of breathing and/or its restoration. In 570 BC a Greek physician, Anaximenes, emphasized that the essence of all life was *"pneuma"* or breath [6]. Hippocrates (460−375 BC) wrote the first directions for intubation in "Treatise on Air" by placing a "cannula into the trachea along the jaw bone so that air can be drawn into the lungs [7]." However, it was Claudius Galen, a physician, in 128 AD, who followed on this by experimentation by breathing into a hollow reed placed in the throats of many different animals, and noted that their chests expanded. Human experimentation was strictly, legally forbidden. In 160 AD, as the physician to the gladiators in the arena, Galen was the first to conclude that the head controlled breathing when he observed that those gladiators who had their heads cut off at the neck ceased breathing immediately and those injured below the neck continued to breathe [8]. His scientific studies through careful dissection in animals became the basis, the “Bible,” for the practice of medicine. He assumed that the anatomy of pigs, apes, dogs, and oxen were the same as in humans. His doctrines were considered so sacrosanct and inviolate by the clergy that their contradiction was punishable by death. This greatly inhibited studies in humans and severely limited the growth of knowledge about breathing in man.

It took more than another thousand years, in 1543, for Andreas Vesalius, a Dutch physician, to dare to do studies in humans. He was a meticulous physician who secretly performed detailed human dissections, despite the church’s prohibitions. This massive work led to his appointment as Professor of Anatomy in Padua at age 23. He was the first to successfully resuscitate a drowning victim by “placing a tube in his throat & bringing him back to life with a return of a pulse.” Previous experimenters found in opening the chest that this caused the lungs to collapse, and was always associated with cessation of heart beats and death. He observed when he opened the chest of animals that “when the lung …collapsed, the beat of the heart and arteries appear wavy, creepy, twisting; but when the lung is inflated at intervals, the motion of the heart and arteries …” resumed, the first description of ventricular fibrillation restored to a regular rhythm with the use of intermittent positive pressure breathing (IPPB). He did this by placing a tube through an “opening” in the trachea of a pig through which he could blow which caused the lung to “rise” and “restore the animal.” This concept of positive pressure breathing lasts to the 21st century, intermittently abandoned, then resurrected. Vesalius stole the body of a criminal, boiled it, and thus acquired the first complete human skeleton. When he was not yet 29-years old, his seven volume book, *de Humani Corporis Fabrica*, printed in 1555, beautifully illustrated by a pupil of Titan, detailed correct human anatomy for the first time, contradicting Galen’s work. This was considered heretical, creating professional and theological storms. The story is told that Vesalius performed an autopsy on a Spanish nobleman and observed that his “heart started to beat again” after he inflated his lungs through a tube placed into the trachea. This, along with his contradicting work, earned him the designation of heretic. Since the Pope had decreed that a heretic was guilty of a form of “spiritual treason” when a system of fines and exile was replaced by execution since 1200, a declared heretic was in mortal danger.It was only because of the wealth of his father and his connections to Charles V, Emperor of Spain and the Netherlands, that he was condemned to a “pilgrimage to the Holy Land” rather than execution. It was on this pilgrimage that his brilliant and audacious career ended in his premature death in a ship wreck off Greece on the Ionian island of Zante. Since the clergy were often the only educated, literate people throughout the middle-ages, their dictums were law. Anyone could be accused of being a traitor who was then summoned before a tribunal, "per inquisitionem," where there was little recourse for self-defense, and sentencing decided. This period, The Inquisition, lasted 800 years, from 1000 to 1800, when countless people were executed, including Joan of Arc, who was executed after torture for heresy in 1431 [9]. This prolonged period dominated by fanatical ignorance with the mortal threat it imposed benefited the clergy and the monarchy both politically and financially and dramatically impeded medical progress [9].

The first recorded attempt of "mechanical" ventilation was in 1550, attributed to Paracelsus, when he used a fire bellows as a device connected to a tube inserted in the patient's mouth to blow air into the lungs to assist breathing, an "IPPB [10]."

Although first mentioned in the bible in Genesis 35:17, midwives have been practicing neonatal resuscitation of apneic infants by mouth-to-mouth breathing since the 15th century although no systematic data were reported as to consequences or the rate of success [11, 12].

Without an efficient means for information dissemination or a common language, it took more than another 100 years for Robert Hooke, an English "Leonardo" in 1667, to apply Paracelsus's IPPB idea experimentally by attaching a pump he made for his mentor, Robert Boyle, to a cut in the trachea of dogs with open thoraces to "blow air in regularly and intermittently to keep them alive," noting the difference in color between venous and arterial blood [10]. Excepting for Vesalius's work, prior to this, opening the chest always resulted in collapse of the lungs, cardiac standstill, and death.

It was John Mayow, an English physician-scientist in 1673, who first conceived and built an external negative pressure ventilator, which consisted of a unit with a bellows and a bladder to pull and expel air, suggesting that this mimicked the action of the inspiratory muscles [13]. While he was also the first to show the necessity of oxygen for life, preceding Priestley, he did not name it. His work remained obscure until 1832.

In Scotland in 1732, W.A. Tossach, a surgeon, reported the miraculous rescue of a suffocated coal-pit miner from the pit when he performed mouth-to-mouth breathing: "I… blowed my breath as hard as I could raising his chest fully" when the heart restarted, after noting that he had to pinch the nostrils to prevent the air from escaping. One hour later the miner began to move and yawn and was said to have walked home after 4 h. His duration of death "was between half an hour and three quarters." Details of the miner's age and subsequent health were not given [14].

It took another 12 years for John Fothergill, in 1744, to successfully revive a drowning victim choosing mouth-to-mouth resuscitation, because he feared lung overdistension with use of the bellows. He also believed that warm rather than cold air would be "more beneficial" that led to its promotion as effective noninvasive positive pressure resuscitation. He founded the British Humane Society in 1750 to promote this method to save lives. A common belief at that time was that a drowned person was already dead, that the lungs were already collapsed and thus not capable of responding to resuscitation. John Fothergill showed that this was not true. Another fear that worked against resuscitation efforts was that a victim brought to a home may obligate the owner for the burial expenses [15].

Twenty-three years later, in 1767, due to the continued frequency of drowning victims in the Netherland waterways, the Society for the Rescue of Drowned Persons, or The Humane Society, was formed to rescue such persons. The first protocols were expounded which included keeping the victims warm, using mouth-to-mouth breathing and the addition of hand compression of the chest or chest and abdomen to “assist expiration” for resuscitation. This inadvertently added cardiac compression to the rescue effort although no records were published as to the rate of its success [16].

Lack of such records and the slowness of information dissemination contributed to developing a litany of other local practices. Many useless ideas were espoused for reviving victims of drowning, as it was thought that strong and stimulating practices could revive a subject. These included being rolled over barrels, thrown over a trotting horse face down, being subjected to loud noises, or having bright lights shone in the eyes, or burned with hot irons. The Humane Society recommended blowing tobacco smoke into the “great bowel” as an “accessory means” to aid resuscitation. When insufficient persons or lack of any implement to blow tobacco smoke were available, induction of vomiting with emetics, pouring warmed wine down the throat, or inducing sneezing with “spirits of quick lime” on a rag placed under the nose were also recommended and practiced with no beneficial outcome. Venesection was promoted as “particularly necessary” if any life returned. Since such accidents occurred ubiquitously, similar Humane Societies were formed in England and other European countries using some combinations of effective and useless techniques [17]. The choice of mouth to mouth or bellows varied by their local popularity or by individual practitioners in the absence of controlled trials.

Between 1772 and 1774, the simultaneous but independent rediscovery of oxygen for its capacity for life support in mice placed under airtight glass domes and to keep a flame lit with “pure,” “vital,” “dephlogisticated air” from which nitrogen (phlogiston) had been removed by Joseph Priestley (English), and Carl Wilhelm Scheele (Swedish), led to the abandonment of mouth-to-mouth efforts in favor of the use of bellows with oxygen for resuscitation. It was thought that more oxygen could be given by the bellows than by mouth-to-mouth attempts. It was the combined work of Joseph Black, isolating carbon dioxide in 1757, Henry Cavendish, isolating hydrogen in 1766 AD, and Daniel Rutherford, isolating nitrogen in 1772 that facilitated the French chemist, Antoine Laurent-Lavoisier, to name the gas Oxygen. Born an aristocrat of independent means, and intensely dedicated to studying respiratory physiology, Lavoisier with Pierre Simon Laplace, in 1780, discovered that the nature of respiration was a process of combustion where oxygen is used and carbon dioxide and water produced. This concept also led Lavoisier to work on public health for the poor because he found the air unclean where they lived. The French Revolution was in full force and for his aristocratic connections and his investment interests his career was cut short by the guillotine. He was labeled “an enemy of the people” in part because his chemistry lab was supported by the King [18]. His work fostered the use of oxygen in resuscitation [19].

During this time in England, John Hunter in 1776 tried to improve on resuscitation efforts by devising a double bellows so that one could be used to blow in “fresh air” or oxygen and the other used to suck out the “bad air;” the first cyclic “ventilator.” This consolidated the use of oxygen for resuscitation. To prevent air from entering the stomach, Hunter applied gentle tracheal pressure to compress the esophagus [20]. He forbade venesection as being useless. The addition of oxygen to mechanical bellows resuscitation was expanded by its promotion by an Englishman, Edmund Goodwyn, MD. He was given a Gold Medal for his acclaimed dissertation “The Connexion of Life and Respiration: On an Experimental Injury Into the Effects on Submersion, Strangulation and Several Kinds of Noxious Airs in Living Animals… and the More Effectual Means of Cure” published in 1805 [21]. This was the first “evidenced-based” study published. It fostered Lord Cathcart, representing Scotland in the House of Lords, to encourage ordinary laymen to use such artificial respiratory resuscitation by offering incremental monetary rewards for saving lives this way based on the extent of action each resuscitator had taken; from a half crown for reporting a drowned victim to a surgeon or to minister, to the largest sum of four guineas for a life saved. Even providing a house for the victim and rescuer was rewarded for “covering expenses” plus one guinea for the “trouble [22].”

The first published hand book for “Life-Saving Measures for Drowning Persons” was in 1796, in Danish, by John Daniel Herbholdt, MD and Carl Gottlob Rafn, botanist. They collaborated on detailed specific resuscitation methods, and described the use for victim retrieval by several types of grappling hooks and boats. What they added was evaluation and critical analysis to their findings that led to similar techniques now still used. Lack of translated copies limited its wider application until the work was translated in 1960 by the Scandinavian Society of Anesthesiologists, on their founding [22].

By 1802, E. Coleman, a Scots veterinary professor, refined a catheter by making it in silver and of larger bore, and introduced it into the trachea to which a bellows was attached and oxygen added. He was also the first to describe the use of electrical current through placing electrodes over the base and the apex of the heart as part of the resuscitation effort [23]. The tripartite successful use of manual bellows or IPPB respiration, with or without intubation, chest-abdominal compression and electrical heart stimulation, innovative then, was overlooked for over a hundred years.

While the fireside bellows of Paracelsus and Hooke had been the “mechanical” tool used, no systematic data were collected as to its success or failure rate, or of any complications, until Leroy d’Etoille, of France, in 1827. He was the first to report a complication when he described its causing “emphysema and tension pneumothorax” and warned against its “improper use [24].” Even though Robert Hooke had suggested that this method of forcing air into the chest might cause “emphysema” in 1667, he provided no data. The lack of volume control using a bellows and the lack of ability to regulate the device for the size and weight of the victims led to Leroy’s challenge to its use. A report of poor survival by Sir Benjamin C. Brodie of the Royal Humane Society in England in 1867 ended this form of positive pressure resuscitation and the societies formed to promote it [25]. Ignorance that proper use could be associated with a better outcome, and discouragement by the high mortality from infections, especially when the trachea was entered, led to the abandonment of this form of IPPB for more than 100 years.

The need for safe, effective resuscitation, however, continued for medical emergencies such as for still born infants, for victims of drowning and for asphixiations from chloroform, fire or other occupational exposures. Manual devices of individual creation were used without systematic study or analysis.

Negative Pressure "Noninvasive" Ventilation (NPNIV)

With the work of John Mayow from the 1670s "lost," between the 1830s through 1925 many scientists/physicians began to think again about "more normal, physiologic" negative pressure methods to support respiration. They set to designing devices that would develop sub-atmospheric or "negative" pressure around the body that would draw air into the lungs for persons with inability to breathe, not just victims of drowning. Early models generally failed, with often prolongation of dying for those so treated by the devices. The failure rate contributed to additional designs even when limited by the absence of available, reliable continuous power to run them.

Four main types of negative pressure devices were designed: the tank ventilator, the "iron lung," the cuirass with a variety of chest shells, and the differential pressure chamber of Sauerbruch.

The tank, the iron lung, and cuirasses will be considered together due to their overlap in development, design, and similarities of action for breathing support, although they are different in their effectiveness for different patient disorders and ages.

The initial devices were cumbersome, were largely manually operated and, except for a few reports, mostly failed. Their perceived persistent need, however, supported the enthusiasm for new designs by many physicians and scientists who collaborated with engineers.

The first unit was made of a rigid wood box housing the whole patient except for the head, around which was an airtight neck collar or "dam" by which intermittent negative pressure, alone or with positive pressure, generated manually or via a mechanically operated pump, using steam, water or electric power, which developed the pressure changes to induce air flow into the chest.

In 1832, Dr. John Dalziel, a Scottish physician from Drumlanrig wrote an easy "On Sleep, and an Apparatus for Promoting Artificial Respiration," the first account of sleep (nocturnal) and artificial respiration [26]. He created the first automatic respirator by designing a box enclosing the seated body with a seal around the head and neck and manually connected to a pair of bellows inside the box, worked from the outside by a piston rod with a one way valve, to develop sub-atmospheric pressure around the thorax so that positive atmospheric pressure caused air to flow into the lungs. The windows at the box's side allowed observation of chest movements. It was not until 1840 that Dr. Robert Lewins of Leith, England, used this model to "produce breathing" in a drowned seaman [26]. He modified it by replacing the bellows with a large syringe. The fact that breathing was restored was measured by the extinguishing of a lit candle under the victim's nostril during exhalation.

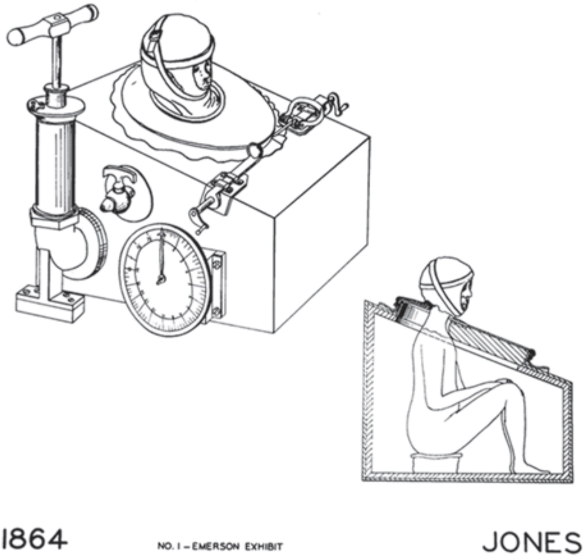

Fig. 2.1 Alfred E. Jones of Lexington, Kentucky patented first American tank respirator. (Used with permission from J. H. Emerson Co.)

Alfred E. Jones from Lexington, Kentucky, USA, following a similar design, patented the first American tank respirator in 1864 also using a large syringe to develop negative pressure for a seated subject. He treated asthma and bronchitis with his device and claimed "cures" for a host of diseases including "paralysis, neuralgia, asthma, bronchitis, rheumatism, dyspepsia, seminal weakness, deafness and … others" when "properly and judiciously" used [27] (Fig. 2.1).

In 1876 Ignez von Hauke from Austria experimented with both continuous positive pressure applied to the mouth via a mask and, initially, continuous negative pressure ventilation for up to 15 min intervals for the treatment of pneumonia, atelectasis, and emphysema. He discovered that intermittent negative pressure ventilation in phase with the patient's inspiration could be used for respiratory failure. He then made an iron cuirass covering the chest with an air-filled rubber edge to "seal." Agitated patients made this device unworkable, which led to the design for the first tank-type respirator, covering the whole body, "*Pneumatische Apparate* [28]." The whole subject was enclosed supine in this tank, including the scalp covered with an elastic cap which was sealed to the tank edge with elastic plaster, leaving the face free. It was hand operated for 2–3 h per "treatment." He used it for many conditions including neonatal asphyxia, atelectasis, pneumonia, tracheitis, croup, and diphtheria. L. Waldenburg, his colleague, reported that it kept a small girl alive for 3 months suffering from "great debilitation and double pneumonia" when she improved, and gained weight. It also "straightened" her rachitic chest wall [29].

In the same year, 1876, Eugene Joseph Woillez from France, designed a workable manually operated negative pressure tank respirator he called a "Spiroscope". Repeating the work of John Mayow, he stated that "the primary reason for the entry of air into the lungs is not the pressure of the air but the expansion of the thoracic

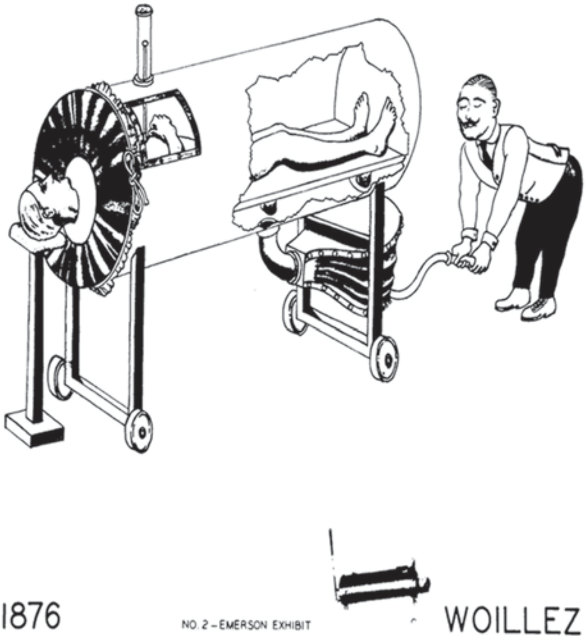

Fig. 2.2 Spirophore of Woillez: a negative pressure tank ventilator which was manually operated with the unique feature of observing chest movements with a rod resting on the patient’s chest. (Used with permission from J. H. Emerson Co.)

cavity by the respiratory muscles.” He then made an improved model encasing the whole body called the “Spirophore” with an adjustable rubber collar to seal around the neck with the head protruding, resting on a shelf, and a sliding bed, which became the prototype for all the negative pressure tank units that followed. A manually operated bellows generated the pressure changes from the opposite end. It had a unique feature, a rod resting perpendicular to the supine patient’s chest which signaled the motion of the chest cage with each breath cycle, thus allowing for its detection [30] (Fig. 2.2). A unit lent to a Dr. Voisin for three drowned victims failed to revive the already dead victims. Woillez refused to patent his unit. His goal was to place these units all along the river Seine for drowning victims but lack of financial support doomed the project, possibly due to the failed attempts.

In 1887 Charles Breuillard, MD of Paris designed an impractical “bath cabinet” for a seated patient which required the patient to operate a valve to shift between vacuum for inhalation and release to atmospheric pressure for exhalation, requiring a conscious subject who could not fall asleep [31]. But it was the first unit to be continuously powered by steam from a boiler heated by a “spirit lamp” rather than manually (Fig. 2.3).

Alexander Graham Bell, the inventor of the telephone, and not a physician, after the death of his 1-day-old son in 1881 designed a metal vacuum jacket in 1882 which developed negative pressures with a separate hand pump to artificially “expand’ the lungs to save lives. It was a unit made of two rigid halves with soft linings held to the chest by a strap, with negative pressure provided by large bellows. He successfully experimented with healthy volunteers. Even after he presented the

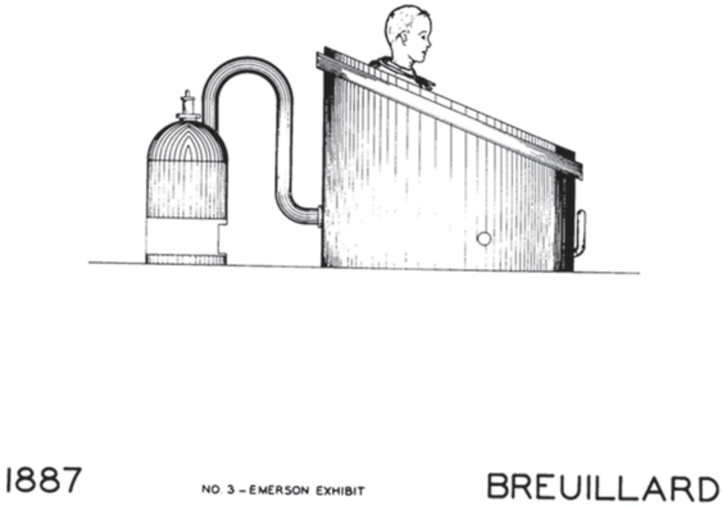

Fig. 2.3 Bath cabinet of Breuillard where the patient had to operate the valve to switch from negative to atmospheric pressure to support breathing. (Used with permission from J. H. Emerson Co.)

results to a meeting of the Advancement of Science and loaned it to someone at the University College in London, however, it generated little interest and went unused, perhaps because Bell was not a physician [32].

In 1889, Dr. Egon Braun of Vienna devised an infant "resuscitator" consisting of a box in which was placed a small supporting plaster mold conforming to an infant's body, with a rubber diaphragm seal around the head, leaving the nose and mouth exposed to air. Through a tube at the base of the box the operator would blow into the pipe to force chest compression, causing the air to exhaust out of the infant, allowing for chest recoil to generate a suction, or negative pressure, to inflate the chest (Fig. 2.4). This was repeated 20–30 times a minute by volunteers and reported to be "completely successful in 50 cases" reported by OW Doe [33].

In 1901, a Hungarian physician, Rudolph Eisenmenger, patented the first portable negative/positive pressure "cuirass" ventilator used for cardiopulmonary arrest from drowning or intoxication, consisting of a two part box enclosing the chest and abdomen, allowing the throat and limbs free. A foot operated bellows was later replaced by motors in 1904 (the "Biomotor") and was reported as "extraordinarily successful" when he reported the resuscitation of a man who had hung himself [34] (Fig. 2.5).

Aside from these issues of negative pressure ventilators to allow for resuscitation, there had been no system that allowed a surgeon to operate on the lung without its collapse until 1904, when Ernst Ferdinand Sauerbruch of Germany designed and built an airtight continuous negative pressure operating room, a giant "pleural space," where the subject's head protruded through a hole, exposed to atmospheric pressure, allowing for inflow of air to the lungs, and where the surgeon, also in the room, could work on a patient with an open chest. It was completely abandoned due

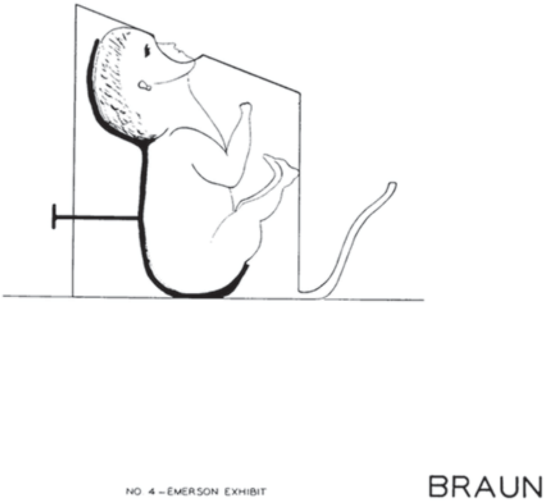

Fig. 2.4 Infant resuscitator of Braun operated by blowing into the box to compress the chest and allow passive recoil for inspiration. (Used with permission from J. H. Emerson Co.)

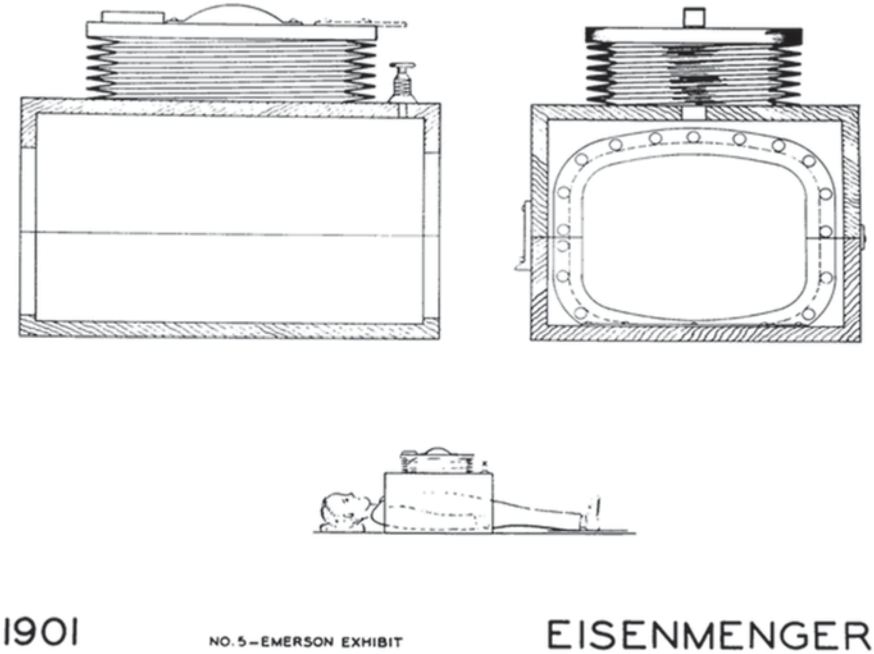

Fig. 2.5 First portable negative/positive pressure when the intial foot operated bellows was replaced by motors and renamed the “Biomotor.” He made a body enclosed unit as well, but this became the forerunner of the cuirass

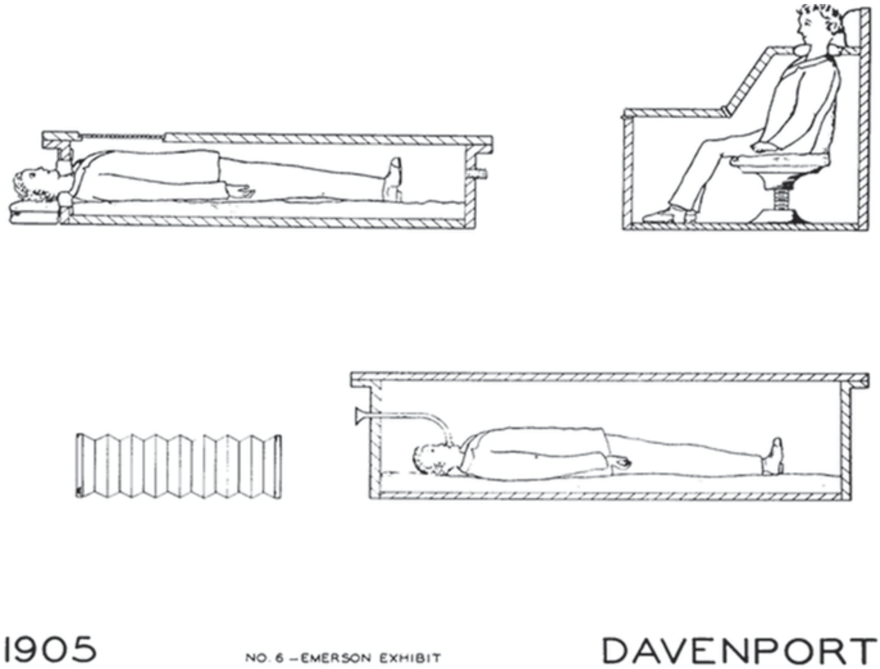

Fig. 2.6 Three models of iron lungs by William Davenport of London. All were manually operated, limiting their utility. (Used with permission from J. H. Emerson Co.)

to the heat in the room for the operators, the lack of space to work, and the inability to talk with the anesthetist. But it encouraged the brothers Willy and Julius Meyer to construct a formidable double operating room in 1909 in New York. It consisted of an outer negative pressure chamber where the patient and the surgeon worked and a positive inner pressure chamber where the anesthetist sat. While considered brilliant at the time, it too failed to be practical and never gained widespread use [35].

In 1905 Dr. William Davenport of London designed several iron lungs: one for a seated subject, one for supine use, and a portable unit modifying the one of Woillez's design. The patients frequently experienced an extended dying process with their use despite the addition of oxygen. Operating the bellows or piston pump to generate negative pressure by hand limited its application [36] (Fig. 2.6).

In 1908, Dr. Peter Lord of Worchester, Massachusetts, patented the design of a respirator room with cyclic pressure changes allowing nurses to work inside it with the patient. Huge pistons in the ceiling provided the negative pressures and the fresh air (Fig. 2.7).

In 1911, Charles Morgan Hammond of Memphis, Tennessee, patented his cabinet respirator or artificial lungs, similar in design to Woillez, having worked on it since 1905. It passed its first clinical trial in 1912, saving more human lives by 1914. He improved on his models for the next 20 years, but for lack of commercial support, its production was limited to Tennessee. When he failed to renew his patent, it expired and his sentinel "first" was abandoned [36] (Fig. 2.8).

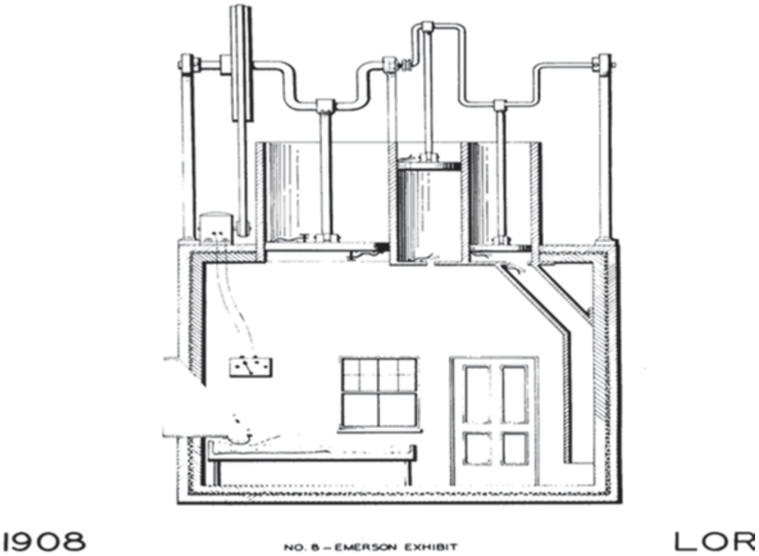

Fig. 2.7 Peter Lord of Worcester, Massachusetts, patented this negative pressure room allowing nurses to work in the room with the patient. (Used with permission from J. H. Emerson Co.)

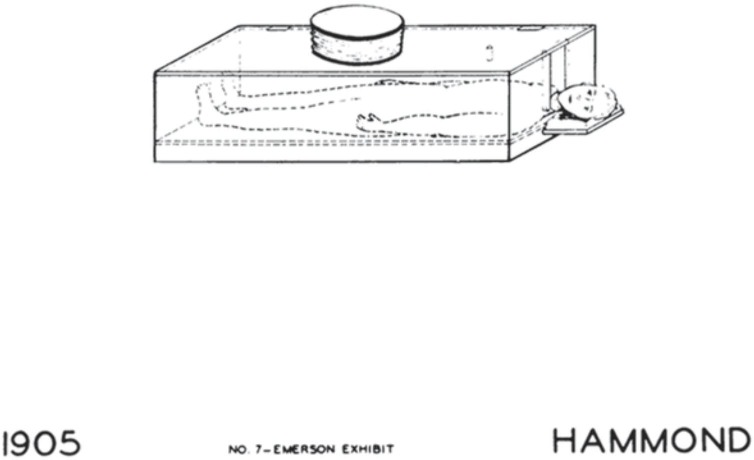

Fig. 2.8 Dr. Charles Morgan Hammond of Memphis, Tennessee designed this unit in 1905, but not patented till 1911. They were similar in design to Woillez, saving its first life in 1912. While saving lives, it was not commercially made and thus not available outside of Tennessee. (Used with permission from J. H. Emerson Co.)

In 1916 a cumbersome, useless unit patented by Melvin L. Severy of Boston was made. Here the patient had to stand in a box, pressing his nose and mouth through triangular openings between two eye slits. It was powered by a bicycle like apparatus of pulleys and electromagnets to create the negative pressures to assist breathing [36] (Fig. 2.9). Severy also designed a negative pressure cuirass.

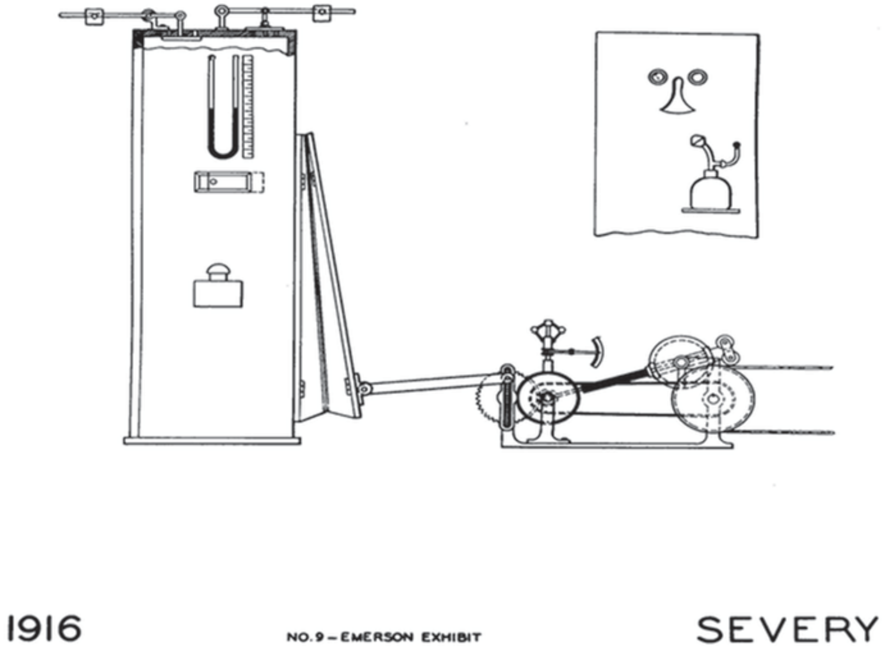

Fig. 2.9 A cumbersome design by Melvin L. Severy of Boston, Massachusetts, where the patient had to stand, pressing his face against one side with apertures for eyes and nose and powered by pulleys and electromagnets outside the *vertical box*. (Used with permission from J. H. Emerson Co.)

In 1918 two physiologists, Felix P. Chillingworth and Ralph Hopkins from Tulane University, reported a new idea, the successful use of an electrically powered body plethysmograph to ventilate tracheotomized dogs by alternating pressures around the body, when studying the effects of lung distension on circulation. With a tracheotomy tube the lack of a neck seal did not matter. They did not realize the potential for using such a negative pressure system for humans but it showed the potential for supporting breathing by alternating pressures around the body and served to inspire Philip Drinker et al. [37].

Poliomyelitis epidemics, while prevalent from the 1870s, resurged in 1916, and were spreading worldwide. Children were the most frequently affected, leading to its designation as the dreaded "Infantile Paralysis." The high mortality rate when breathing was affected was soon recognized and spurred the development of efforts to reverse the near 100 % mortality from respiratory failure. Many negative pressure ventilator innovations followed, spurred by this need, but poor communication and/or an absence of training and resources limited their application.

W. Steuart in South Africa, in 1918, made an airtight, rubber-lined rigid wooden box, with a mattress, that was applied over the chest and abdomen. It was the first workable cuirass, through which a variable speed motor drove a bellows rhythmically to produce negative pressures. Tidal breath and minute volume were adjustable

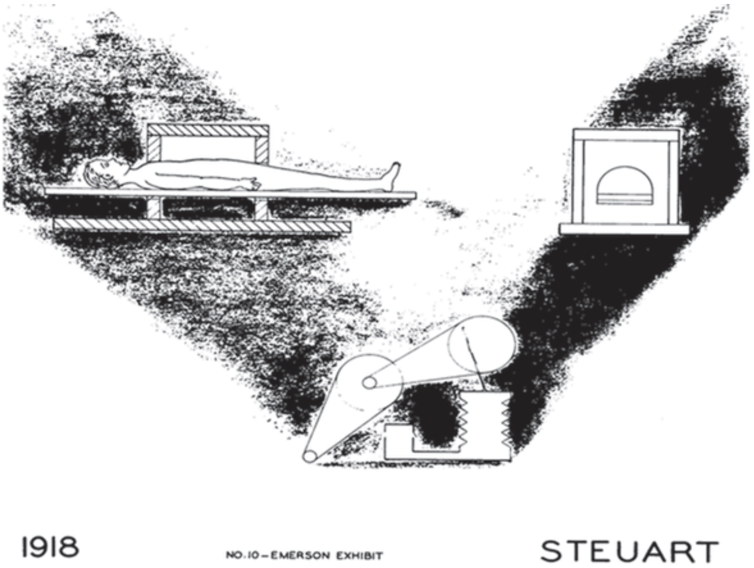

Fig. 2.10 An airtight wooden box made by South African, W. Steuart, the first workable cuirass where a variable speed with a rhythmic motor produced the pressure changes where tidal breath and minute ventilation could be set. (Used with permission from J. H. Emerson Co.)

along with valves that could adjust the amount of negative pressure. A glass panel allowed observation and the top of the box could be removed quickly in case of need for patient access. Steuart presented this work to the South African Medical Society. He was unable to conduct a clinical trial because the last patient died before he completed the work. However, the principal of longer term artificial respiratory support where breathing could be individually adjusted had now been introduced for the first time [38] (Fig. 2.10).

In 1900 Dr. Tursten Thunberg of Lund, Sweden, developed a truly novel concept: ventilating without chest movement. He designed a "Barospirator," producing the final sarcophagus-like version in 1920. It was a tank large enough to encase the whole patient. His idea was to limit chest motion to a minimum. His was the first mechanical ventilator applied successfully for "long-term" use of several months [39] (Fig. 2.11). Its first success was to save a patient from paralyzing poliomyelitis [40]. A. L. Barach, in order to make the chest cage completely immobile to "rest" the lungs to allow advanced tuberculosis cavities to "close," modified the Barospirator by making an upper section, encasing the head, and a lower body section, separated by a fine mesh nickel plated screen, producing cyclic, equal pressures both inside and outside the chest so that air would flow with no chest motion. He separated the head in his Barospirator because of a delay in pressure transfer due to airflow resistance from the upper airways, which allowed continued, albeit reduced, chest movements, and thus not total rest. He reported applying this therapy for 12 h per day and felt that it could take the place of induced pneumothorax, without or with the instilling of space occupying materials in the pleural cavity to collapse the

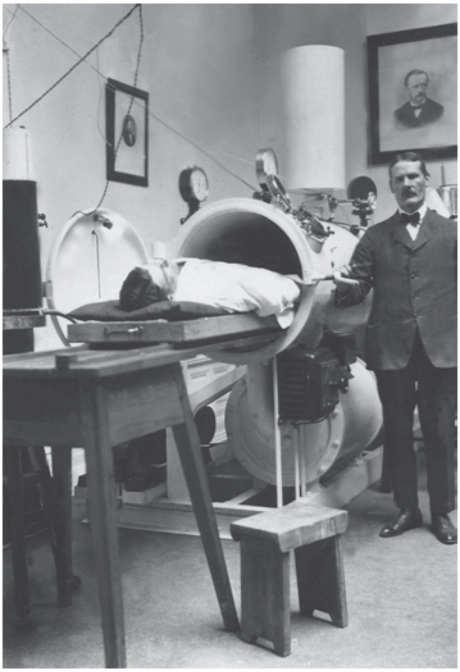

Fig. 2.11 Dr. Tursten Thunberg of Sweden with his “Barospirator,” developed to ventilate with almost no chest movements, put to use in 1920. It was adapted by Alvin L. Barach, MD, to immobilize the chest for the treatment of cavitary tuberculosis while breathing was supported with continuous negative and positive pressures. (Used with permission from the South Swedish Society for the History of Medicine)

cavitated lungs, all before the availability of chemo therapy for tuberculosis [41]. The effectiveness of Streptomycin and Para-aminosalicylic acid in 1945-46 ended the need for this.

In 1926, Wilhelm Schwake of Germany patented a totally impractical pneumatic chamber in which the patient had to stand and use his own hands to move a large bellows, comprising the whole side of the box, to generate negative pressure to “draw out the gaseous by-products” [36] (Fig. 2.12).

In New York that same year, the Consolidated Gas Company faced the need for resuscitation and respiratory support for an “alarming number” of electric shock, carbon monoxide gas, and smoke inhalation asphyxiated workers. They engaged Dr. Cecil K. Drinker, Professor of Physiology at the Harvard School of Public Health, to help these victims. Dr. Drinker called on his brother engineer Philip A. Drinker, who worked with pediatrician Dr. Charles F. McKhann, III, and physiologist Dr. Louis Agassiz Shaw. Like Chillingworth and Hopkins, they had been experimenting with placing intact curare-paralyzed cats in iron boxes, with only the head protruding through a rubber, now airtight, collar. To move their thoraces, negative pressures were generated by a hand-operated syringe and later by a hand-operated cylinder piston pump causing inspiration when the air was sucked out. Pressure measurements in the plethysmograph, correlated with volumes of air moved in the cats. By 1927 they showed that, by alternating suction and release, the cats could be kept alive for several hours [42]. Such success, and the demands from the polio epidemic, led to their constructing a unit large enough to accommodate a human.

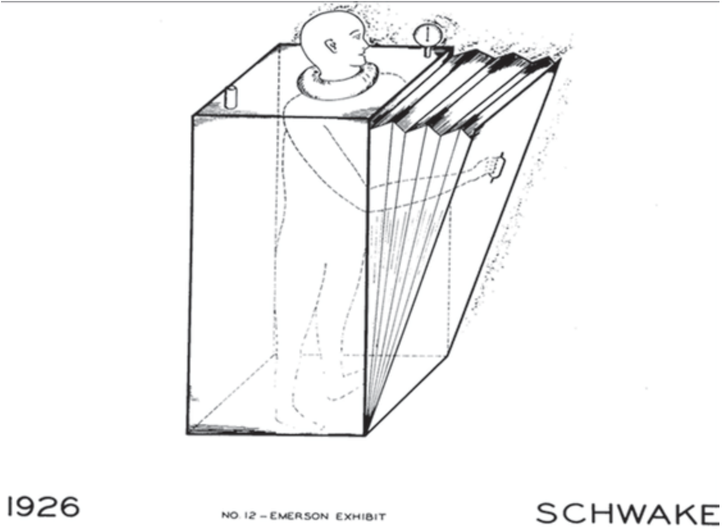

Fig. 2.12 Wilhelm Schwake patented this pneumatic chamber which required the patient to operate a large bellows to generate negative pressure. The patient can see the pressures generated by the gauge placed near the face. (Used with permission from J. H. Emerson Co.)

They salvaged materials to make the first unit for about $ 500.00 ($ 6579 in 2013 US dollars). It was a metal cylinder with one end for the head to protrude with the neck encircled by an airtight collar. The other end had a piston pump through which pressure changes were generated [43]. Reliable electricity became available first on the two coasts in the USA about 1926; [44, 45] this allowed the unit to continuously produce alternating positive and negative pressures by a series of valves, thus moving the thorax. They used the units on themselves and on a diener recruited from the laboratory. Harvey Cushing was the "audience" for these experiments. Drinker himself was hyperventilated by this device and even though he did not resume breathing for 4 min he felt no anxiety as he "simply waited until he felt the need to take a breath." Their first patient was a patient of Dr. McKhann, an 8-year-old girl with polio who was first acclimated to the noise of the unit by placing it in her room over night. By morning she was cyanotic and comatose. She was placed in the chamber and regained consciousness in several minutes and was said to have asked for ice cream a short time later [46]. Even though she died of pneumonia several days later, this dramatic success for the first reported human use of the iron lung, a device that supported breathing by externally applied alternating pressures, and the terrible polio epidemics, led to their widespread use. The funding for 14 more units was provided by the New York Consolidated Gas Co; one of these units was donated to Bellevue Hospital in New York City in 1929 when its use saved an unconscious apneic student nurse from an accidental drug overdose, a now expanded clinical indication for such ventilatory support. It was then applied to a Harvard student who had contracted poliomyelitis in Cambridge. This allowed him to gradually regain his breathing ability, to finish school, and go on to a full career. This was the first

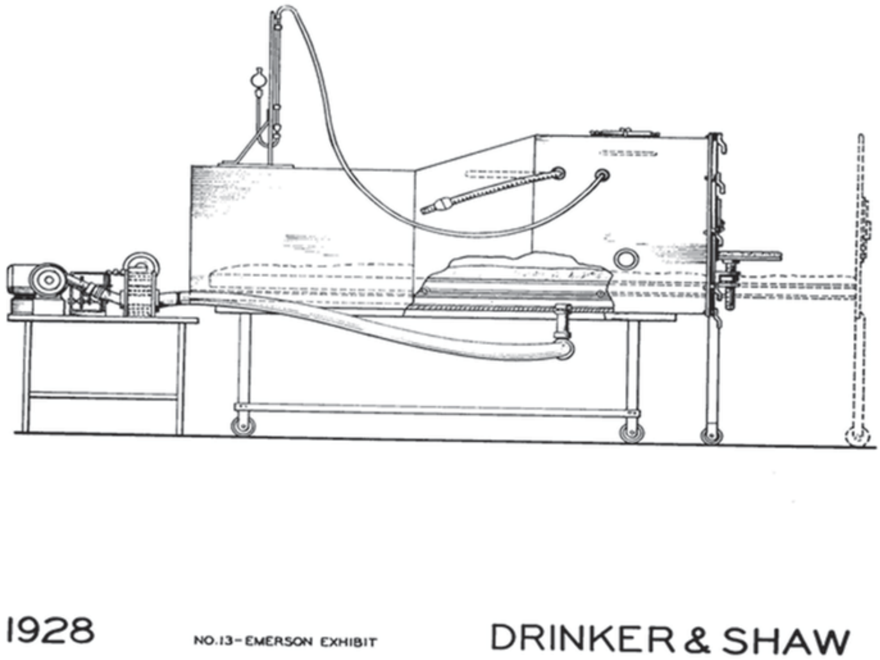

Fig. 2.13 The Drinker-Shaw model of the first successfully used iron lung powered by electricity designed by engineer Philip Drinker and physiologist William Shaw. (Used with permission from J. H. Emerson Co.)

documented instance of private corporate financial support for research that led to direct and wide spread clinical application, i.e., “translational” medicine, becoming the model for such enterprises since. The incredible success of the Drinker-Shaw iron lung tank ventilator, in conjunction with the availability of reliable electric power across the whole country, and the escalating number of polio victims (from 20,000 to 60,000 cases per annum [47], affecting mostly children), set in motion the demand for mass production of the now-named Drinker Respirator. Warren E. Collins Company of Braintree, Massachusetts, was commissioned to make the units but their cost of $2000.00 each ($ 21,444 in 2013 US dollars) equaling the cost of two automobiles in 1929, limited their distribution (Fig. 2.13).

In 1930, James L. Wilson, desperate to treat children with paralysis from polio, worked with Drinker to have the tank redesigned so many children could be treated in a “Respiratory Center,” allowing concentrated nursing care, although not knowing if recovery would ensue. Most children recovered and no longer required such ventilatory support, but the ones who did not recover lived in their tank ventilators, sometimes for more than 50 years. This was the beginning of designated respiratory care units for larger numbers of patients, the pre-intensive care units of today. As the key organizer, Wilson recruited The March of Dimes to establish 13 such centers across the USA [48] (Fig. 2.14).

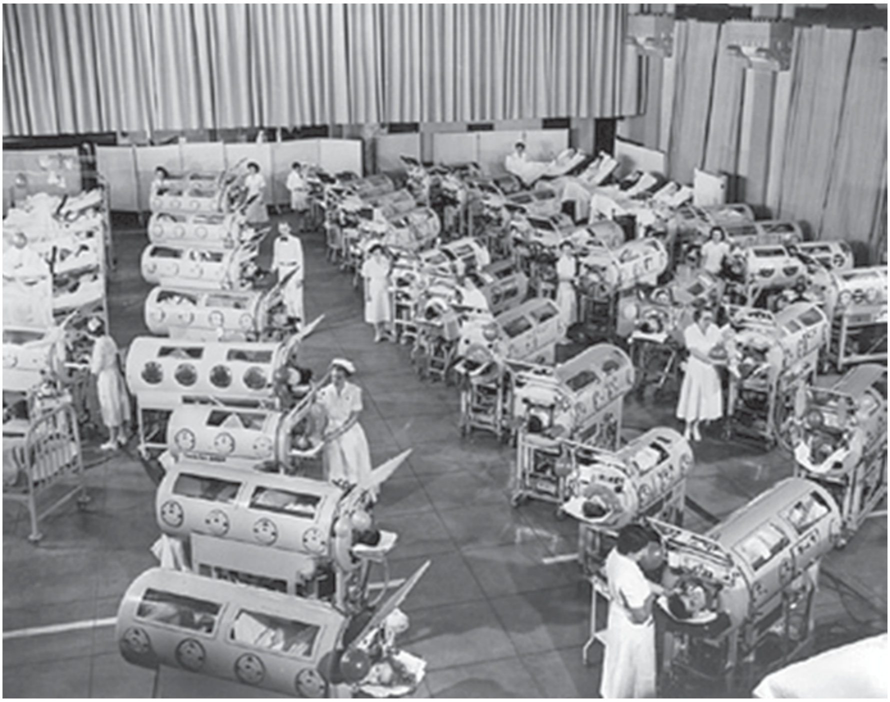

Fig. 2.14 Respiratory Center (aka: TANK FARMS"), Rancho Los Amigos, San Diego, 1953. These were dedicated units for polio patients where centralizing care into one room made it more efficient to care for the large numbers of patients. These were largely supplied with Emerson units. James L. Wilson, MD, recruited the newly formed March of Dimes to support the establishment of some 19 centers across the country. (Used with permission from Post-Polio Health International)

The polio epidemic reached its "worst in the 20th century" in 1931. The Drinker unit was bulky and complex, and its cumbersome design making it difficult to use, coupled with the unaffordable cost, inspired John Haven Emerson, an engineer in Cambridge, Massachusetts and the grandson of poet Ralph Waldo Emerson, to simplify, modify, and improve the unit at half the cost in 1931. In addition to a sleeker design, his additional innovation was adding an airtight, transparent dome for the head for the application of IPPB so the body of the unit could be opened for unhurried nursing care while the patient was continuously supported noninvasively [50]. This unit had several glass side ports and larger rectangular metal doors on both sides through which care could be administered, blood gases and bloods drawn, and clinical observations made. He made a thick leather diaphragm to move the air and powered it with a standard vacuum cleaner pump to which a cyclic feature was added. Two vacuum pumps could be connected in series to amplify the pressures if needed. It could also be manually operated should there be a power failure, not uncommon at that time. The adult unit was 33"wide × 92"long × 56" high, and despite the weights for varying sizes from 640 to 800 lbs (290–337 kg), it was a great success (Fig. 2.15a, 2.15b an opened unit; 2–15 C a unit with a transparent

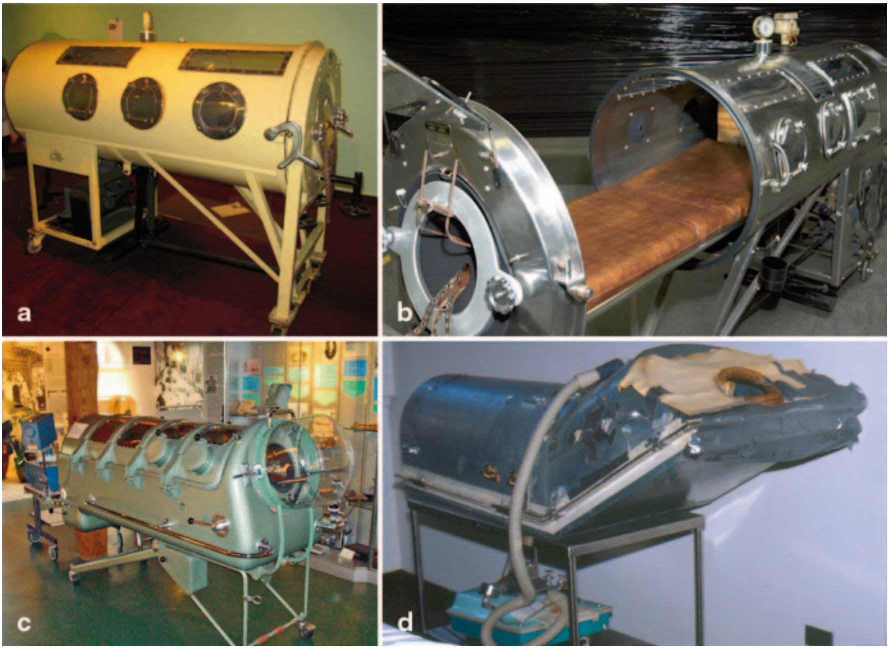

Fig. 2.15 **a** The Emerson iron lung made for half the price of the Drinker Shaw model in 1931 at the height of the polio epidemics. It weighed some 224 lbs. (102 kg). Children's models were also made by Emerson. The gauge reflecting the pressure changes is on top of the uint. **b** The Emerson iron lung open showing the neck hole with the foam cushion and a slide out cushioned bed with a pressure gauge on *top*, with the windows and the several side ports to allow nursing care and monitoring. There was a mirror *above* the patient's head so visitors to the bedside could be seen by the patient. **c** Iron lung housed in the Gütersloh Museum, Germany: Illustrating a transparent dome for positive pressure breathing when the unit is opened (Emerson) or for administering oxygen and/or CO_2 to "stimulate breathing" (Krogh). Used with permission from Post-Polio Health International. **d** Emerson customized iron lung used by a Judge for over 40 years who had had polio. A modified Hoover Vacuum pump sitting underneath was the power source. Its reapplication in the surgical recovery unit after retroperitoneal cancer surgery allowed vigorous diuresis and extubation with discharge home

dome for the head; 2-15D Custom made model for a judge). Emerson deliberately decided not to patent his design because he wanted to make the units affordable and available as soon as needed throughout the country [51]. Their use was rapidly expanded where the new "respiratory centers" could accommodate many patients into single large rooms for multiple patients (aka "Tank Farms") and became the first dedicated respiratory care units (Fig. 2.14). A lawsuit by Drinker for infringement of patent rights failed after John Emerson published a pamphlet with a series of pictures depicting *The Evolution of "Iron Lungs*" with previously designed negative pressure tank ventilators long before the Drinker model [49]. This pamphlet is the source for some of the figures in this chapter. Some of the patients, who either were unable to regain independent breathing function or only regained partial function while awake, were continuously or nocturnally supported for more than 60 years in their iron lungs [52, 53]. One such woman, who contracted polio in 1955 at age 5 just before the polio vaccine, is still using negative pressure ventilation 58 years later. She wrote a Haiku poem: "The story of Jonah—narrow my bed in the belly of this iron lung yet wide enough for the dreams any child would chase [54]." The Emerson Tank Respirator needed only "greasing of the motor and a new fan belt once a year" to maintain reliable function for many years [55].

Another cheaper innovation was designed in Denmark in 1931 by August Krogh, a physiologist, who, as with Cecil Drinker, was concerned that the tight neck collar would limit blood flow to the head. After seeing the Drinker model work in New York, and with bulk and costs prohibitive for transporting the iron lung to Denmark, he "simplified" and improved on it by using water to power it from city pipes. A piston cylinder, acting on a large spirometer bell, created reciprocating movements from alternating the water between the upper and lower compartments of the piston to effect breathing cycles. The temperature inside the tank could be regulated by a water jacket. Another innovation was that the head could be placed in a 15° head down position and could be encased in a hood through which oxygen or a mixture of 95 % oxygen and 5 % carbon dioxide would be administered to "stimulate" respiration (Fig. 2.15c). Mortality fell to 30 % using this ventilator. He also made an infant-sized version and a rocking stretcher, a forerunner of the Rocking Bed [56]. John Emerson advanced the Rocking Bed design and manufactured and distributed an electrically operated one used for long-term (for as long as 45 years) intermittent noninvasive ventilatory support for polio and other patients with persistent diaphragmatic paralysis [57] (Fig. 2.24). He also designed a Motion Bed to prevent skin decubitus ulcers and lung atelectasis, and to enhance circulation, in bed-ridden patients. We reported the use of the Emerson Rocking Bed for patients who developed diaphragmatic paralysis after open heart surgery, allowing for extubation or tracheostomy decannulation and recovery at home [58].

Chance favors the prepared mind, and with the extensive worldwide polio epidemics there was an increasing demand for negative pressure ventilators. In England in 1938, resources were contributed by William Morris (aka Lord Nuffield), an engineer-philanthropist, and owner of the Morris auto factory. After reading a newspaper headline that "Iron Lung Arrives Too Late" to save the life of a young woman, he conferred with Sir Robert Macintosh, head of the Department of Anesthesia at Oxford, who had earlier impressed him with a film of the Both Respirator's capacity to perform artificial respiration. This unit was invented in 1937 by the brothers Edward and Donald Both in Adelaide, Australia. It was made from plywood, making it lighter, easier to transport, and cheaper than earlier versions. Edward had gone to England to sell an electrocardiograph he designed. Learning about the polio epidemic while there, he offered his design of the *Both Portable Cabinet Respirator*, which was quickly accepted, manufactured locally, and put into use (Fig. 2.16). After Edward built a unit for Robert Macintosh, a short film was made. This was the film that inspired the philanthropic act of Lord Nuffield when he offered to manufacture 5000 Both Respirator units at a personal cost of £ 500,000 (equal to $ 2.5 million in 1938 and $ 32.7 million in 2013 US dollars) so that one unit could be given to every hospital in the UK, giving him "the pleasure"

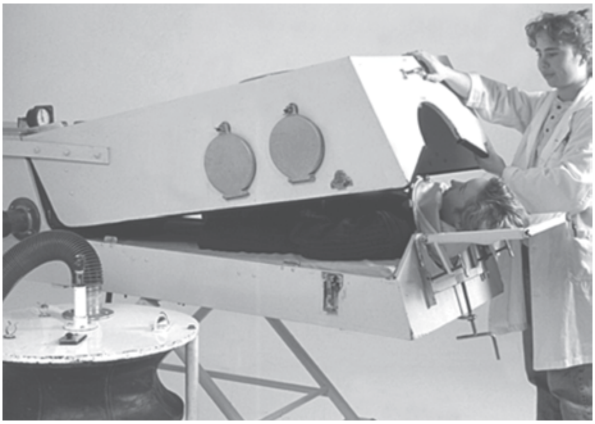

Fig. 2.16 The Both portable cabinet "Alligator" respirator at the National Museum in Australia. It was made of wood, designed by brothers Edward and Donald Both of Australia in 1937. Its use was expanded by the philanthropy of William Morris, owner of the Morris auto factory, by his gift of £ 500,000 to provide one to every hospital in the UK in 1938. (Used with permission from Post-Polio Health International)

of saving lives. Nuffield entrusted Macintosh to accomplish their distribution, and for teaching their use through daily demonstrations at the Radcliffe Clinic. By 1939, only 1 year later, more than 1700 Both Respirators had been allocated and its use taught throughout the UK. This heralded the extensive application for successful prolonged intervention for breathing inadequacies saving countless lives with NPNIV. Since Macintosh was an anesthesiologist, he conceived of using the Both Respirator to manage postoperative patients as well. He was the first, in 1940, and then with Mushin and Faux, in 1944, to demonstrate the successful prevention of postoperative atelectasis by use of the Both Respirator. This gave birth to the advent of "critical care" medicine to provide respiratory support, and eventually to critical care units [59, 60]. Space needs and nursing care demands, however, remained impediments to the widespread use of such still bulky equipment.

In 1952, an English doctor-engineer, George Thomas Smith-Clarke, made the Cape Warwick iron lung with a head down option, redesigning it from the Both model, which was then widely used in England for polio patients [61] (Fig. 2.17).

In 1961, W. Howlett Keheller, MD, modified the design of the iron lung so it could be rotated 180°, allowing for automatic turning, to treat or prevent atelectasis, successfully treating three patients with neuromuscular respiratory weakness (2 post-polio, 1 Guillain-Barre) who developed life threatening airway secretion retention associated with atelectasis [62].

In 1975, Sunny Weingarten, a polio survivor from age 7 ½, designed a lighter (100 lbs; 45.5 kg), more portable tank, a "Porta-Lung." It was made from fiberglass, in four sizes, the extra small for children at 30" length and up to 71" for adults. The unit had flexibility for clinical use in that it had several brands of vacuum pumps accommodating adjustment of pressures ranging from +20 to −60 cm H_2O, respiratory rates from 4 to 60/min, and variable inspiratory/expiratory ratios (Fig. 2.18). He traveled over 50,000 miles in his van using it in all the then 48 states. He died at age 70 in 2012 having been on ventilator support for life, initially full time, then nocturnal only, and finally back to full time, switching to positive pressure as he aged before his death [63]. The Porta-Lung was patented and FDA approved, and

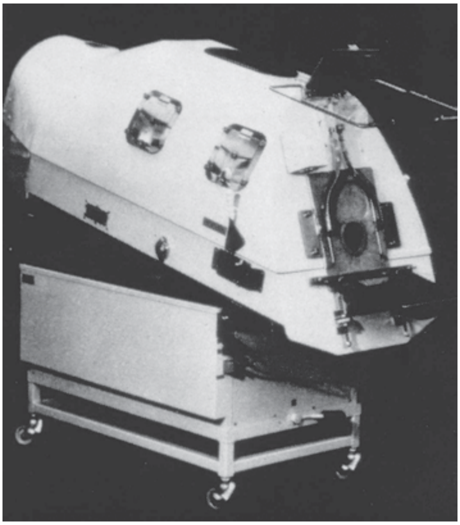

Fig. 2.17 The Cape Warwick iron lung made in England in 1952. Designed to allow the head tilt down position for pulmonary toilette. Some are still in use. (Used with permission from Post-Polio Health International)

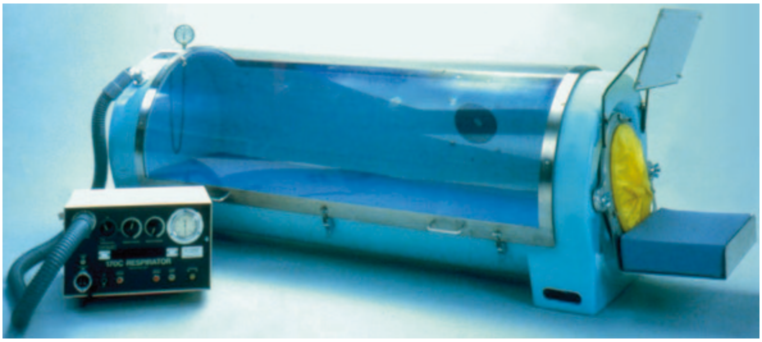

Fig. 2.18 In 1975, Sunny Weingarten designed a fiberglass model, the Porta-Lung, making it lighter (100 lbs./45.5 kg) to allow easy transportation with a larger range of pressures (+20 to−60 cm H_2O) and rates from 4 to 60/min and variable I:E ratios. A life care pump is used here

is still being used by patients due to their comfort and reliability [64]. The problem with this unit currently is replacing worn out negative pressure pumps, since the five that were available are no longer manufactured [65].

Others, especially Italian doctors, remain active in using negative pressure noninvasive ventilation (NPNIV), and some have made their own version of a tank. Drs. Sauret and his associates [66], and Corrado and Gorini summarized in 2002 the literature on the use of both NPNIV and noninvasive positive pressure ventilation (NPPV) for both acute and chronic respiratory failure, which consisted in mostly uncontrolled reports. The need for endotracheal intubation or tracheotomy was the primary end point assessed, and was not different between patients who used NPNIV or NPPV. Mortality was also no different [67–70].

Complications from iron lung use slowly became apparent with their wider use. It stemmed from their bulk and weight, taking up so much space in a hospital room that floors had to be reinforced to support many tanks (Fig. 2.14). The patients felt isolated, resulting in claustrophobia, disorientation, and loneliness for many as well as inhibiting good nursing care. One such patient of mine, a post-polio wheelchair-dependent judge in New York City, started having recurring nightmares of being "trapped" in the iron lung when he developed right heart failure from chronic hypoventilation 40 years later [71]. Using the Pneumosuit (Nu-Mo suit), instead, reversed the hypoventilation, and restored his capacity to work. Vital signs in the iron lung were cumbersome to measure, providing personal hygiene was difficult, and frequent turning to prevent decubitus ulcers was necessary. Even though the Emerson transparent dome reduced these problems for some of the time, air leak prevention from the tightness of the collar created neck skin abrasions and headaches. Patients experienced distress on hearing their own pulses from the tight collars. When less tight, the air leak made them feel cold, especially if they had total body paralysis as well. Some had difficulty initially learning how to synchronize their swallowing while in the iron lung. Aspiration due to the imposed supine posture would occur, at times resulting in death from pneumonia despite the support. Inadequate airways clearance, absent cough capacity, and lack of effective antibiotics contributed to such lethal pneumonias [72]. While some patients successfully used these units in their homes for many years, such units could not be housed there for many patients, particularly at the time that home care was not yet a developed discipline. The polio epidemics and his own polio inspired Franklin Delano Roosevelt (FDR) with friends to found The March of Dimes to provide the financial support for many patients in hospitals, in rehabilitation units, in the homes, and for scientific research for the polio vaccines. In fact it was FDR, focused on regaining the use of his legs after polio, who helped to establish the first rehabilitation unit in Warm Springs, Georgia, dedicated to the care and recovery of polio patients in 1924 [73].

These problems furthered the design of negative pressure devices that only covered the chest or the chest and abdomen called cuirasses, or chest shells, due to their resemblance to medieval protective chest armor made of leather or metal which covered the neck to the waist. While Steuart's model was designed in 1918 it was not widely known or used. The design of the earlier cuirass models also allowed for only the anterior expansion of the chest wall due to its ending at the waist which limited diaphragmatic descent by compressing the anterior abdominal wall during inspiration. Lateral expansion was severely limited when the unit was flush with the lateral chest walls. The apices were usually excluded by the shell's upper configuration and necessary seal. Other shell designs that ended at the umbilicus or just above the pubis allowed for more diaphragmatic descent. If the metabolic requirements were low, the neck to waist model could be adequate. The advantages were their portability, lower cost, and the freeing of the extremities and pelvis with greater mobility and less claustrophobia. Some patients were able to be adequately ventilated in a near sitting position with such units, allowing for more daytime use. Some combined it with positive pressure using a mouth piece or lip-seal [74]. In fact, one of my chronic obstructive pulmonary disease (COPD) patients who had intractable dyspnea and chronic hypercapnic respiratory failure used NPNIV via a Nu-Mo suit nightly, achieving eucapnia, and went home to Brazil (Fig. 2.23). She worsened 2 years later. On her reevaluation, she had gained 35 lbs. This resulted in upper airways obstruction while using nocturnal NPNIV as Goldstein and Levy had reported [75, 76]. Increasing negative pressure from −35 to −40 cm H_2O worsened this. She refused any other form of support. Adding +5 cm H_2O nasal continuous positive airway pressure (CPAP) circumvented the upper airway obstruction, and she went home successfully using her Nu-Mo suit NPNIV and nasal CPAP.

Many cuirass models were made in several countries including the USA, UK, France, and Sweden. The first units, made by Ignez von Hauke, of Austria, who also made a body unit, in 1874, and Alexandra Graham Bell in 1882, were largely unused by the medical community. Rudolph Eisenmenger of Hungary developed his "Eisenmenger Biomotor" in 1927 made into a "simple, two-part box" and half horse power driven motor, which encased the patient's chest or abdomen (see Fig. 2.6). Suction allowed diaphragm descent for inspiration and its soft rubber lining pushed positive pressure into the abdomen during exhalation, augmenting the next breath. This unit was used for both polio patients and for patients with heart failure and acclaimed a "success [77]."

In 1930 Stille-Werner of Stockholm, Sweden, manufactured cuirasses designed by Sahlin at the Physiologic Institute at Lund. A sheet metal cuirass, available in three sizes, with a rubber-lined edge, was bolted onto an operating table into which the patient was placed, where both negative and positive pressures were generated by a power unit [78]. Bergman reported survival of 127 (15.4 %) polio patients from the 827 in whom it was used, including one who was supported for 7 months [79] (Fig. 2.19).

At the same time P. Peterson in Lund created a cuirass, the "Pulsatorgurtel," for resuscitation at baths (swimming pools). Its complexity, however, doomed its use [80].

The polio epidemic in Victoria, Australia, in 1937 saw the rise of use of tank respirators from 2 to 200. The observed need inspired Aubrey Burstal, Professor of Engineering at the University of Melbourne, to make a smaller "jacket" version with a thorax shaped aluminum shell with a sponge rubber vest for children. Rubber sleeves and collar rendered it airtight (Fig. 2.20). The pump from the Drinker/Emerson tank was used as the power source, and due to the small volumes of the jackets, proved to be able to power several jackets at a time by one attaching flexible hoses from the jackets through holes drilled in the tank. They were much cheaper, and allowed for easy sterilization of the units and the nursing of patients, especially those with splints, in standard hospital beds. The disadvantages were getting an airtight seal and the time, ~7 min, it took to apply it to the patients, made longer, ~10–12 min, if the patients had splints on, making it somewhat hazardous for those who could not tolerate the absence of breathing support for that amount of time [81].

Dr. Andrew Topping from the London County Council (LCC) was given a Burstal jacket which he redesigned. Rather than being placed over the head of a patient, it

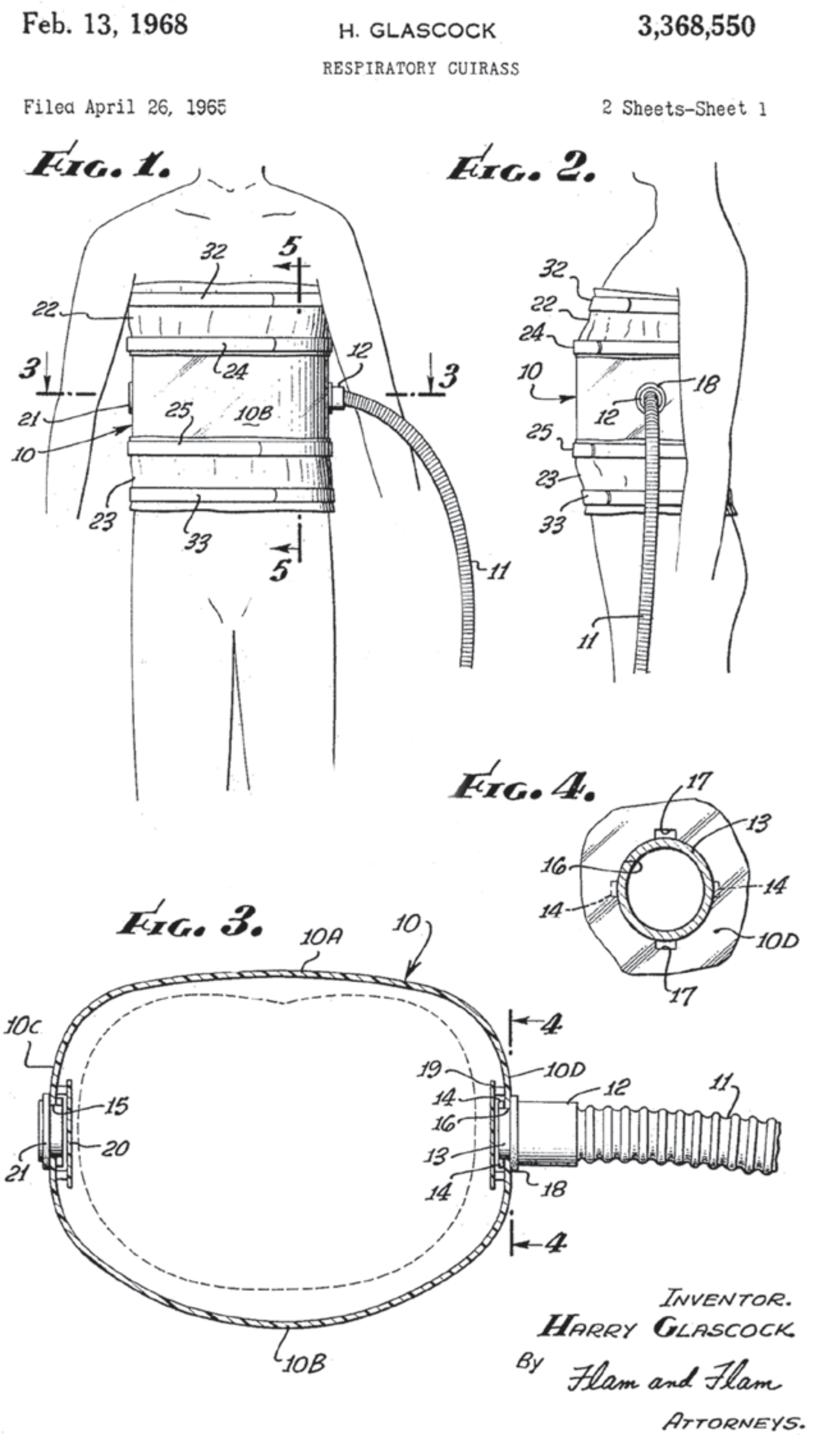

Fig. 2.19 Sahlin aluminum chest cuirass which was lighter in weight, closer to the chest wall, not allowing much lateral chest wall motion nor accommodate chest wall deformities

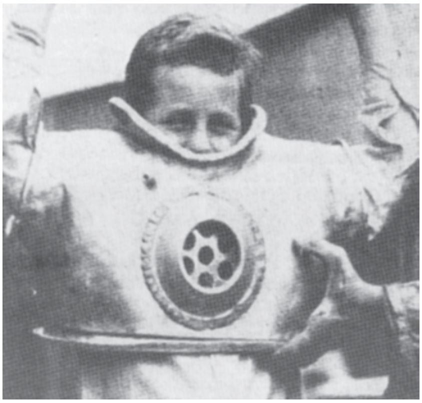

Fig. 2.20 The Burstall jacket: An aluminum shell for children powered by an Emerson tank through which several children could be connected to one tank. It took 7–12 min to place the child in the unit, lengthened by the presence of limb splints which could be too long for some children with severe breathing compromise. (Used with permission from Elsevier)

was made of two halves bolted together with wing nuts. Better seals around the arm holes made it more comfortable and freer for the patient. Its own power unit of 1/8 horse power drove a bellows with a set rate of 20 per min with negative pressures up to -25 cm H_2O, controlled by a variable leak valve on the cuirass. Should power fail, a hand driven mechanism could take over [82, 83].

The demand for resources in World War II put a brake on any further developments of any negative pressure ventilators. In 1947, a Council of Physical Medicine was formed which was the first to establish criteria for approval for use for all American cuirass ventilators including “efficiency, size, range, portability, standard of power unit, patient comfort…” and even “methods of advertising.” Units failing testing failed approval, the first quality control [84].

From 1947 through 1950, as polio continued to infect scores of people, more cuirasses were designed and manufactured. One was Blanchard’s Portable Plastic Respirator jacket from Los Angeles, driven by an electrically powered bellows, in 1947. Another, in 1949, the Chestspirator, had an innovation as the first thoracoabdominal cuirass covering the entire anterior body from the clavicles to the pelvis, allowing for larger tidal volumes [78]. From Denver, specifically from the Monaghan Company in 1949, came more sizes, now six, with pneumatic rubber seals which could be individually adjusted for each patient [85]. These were the first units I learned to use during my fellowship for patients with acute respiratory failure from overwhelming pneumonia and for patients with chronic respiratory failure due to COPD, not just from polio, with variable success.

The next modification, in 1950 from New York, was the Fairchild-Huxley Chest Respirator which was offered in both chest and thoracoabdominal models, each in three sizes. They had adjustable feet which prevented their downward movement during use. A first, an alarm system for power failure and leaks, was a unique added feature [85] (Fig. 2.21a Fairchild-Huxley model). Other models followed (Fig. 2.21b: Kifa; Fig. 2.21c: Monaghan).

Bulbar polio had been uniformly fatal until tracheotomy was performed, first in the USA, to manage such individuals. A sloping front tank was designed to accommodate the tracheotomy until the Monaghan cuirass was successfully employed to support three patients when other models failed [82]. This introduced a new type

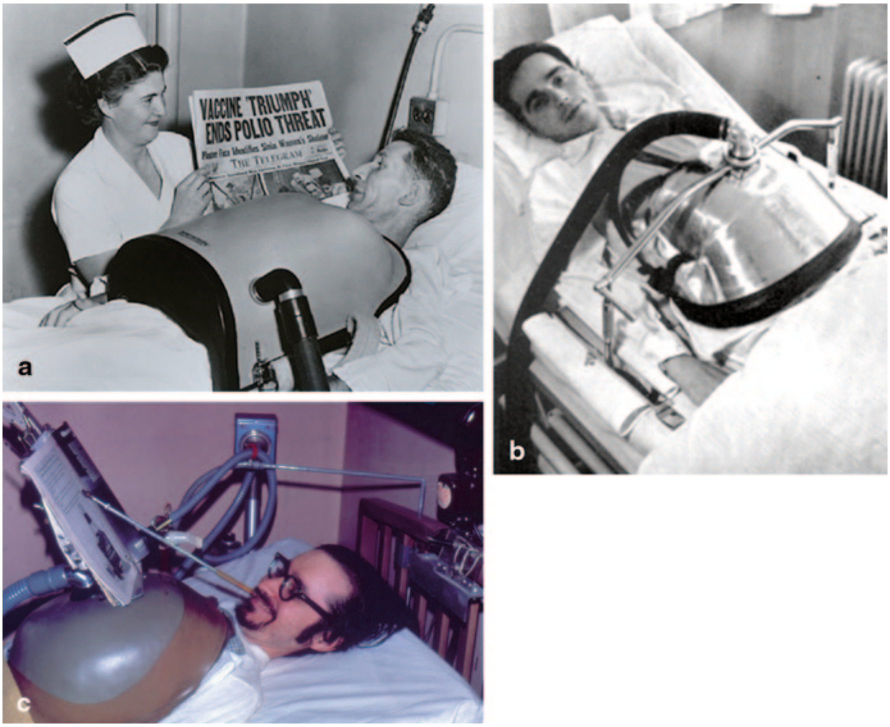

Fig. 2.21 **a** The Fairchild-Huxley cuirass from 1940 to 1950s: This one extends from the neck to the lower abdomen, effecting larger tidal breaths. The irony of the news headline for the patient is clear. Used with permission from J. H. Emerson Co. **b** The Kifa cuirass: note the low lying shell which compresses half of the upper chest cage during inspiration. Effective when metabolic loads were low as the Kifa so applied allowed only 1° of chest expansion by diaphragm descent anteriorly. Used with permission from Elsevier. **c** A patient with complete post polio complete quadriplegia using a Monahagn Chest Shell cuirass for sleep and a Pneumobelt in his wheelchair during the day for his lifetime from age 14 to age 64. He worked every day, running his own company, and survived past the 6th decade, using his mouth to write. His legislative efforts allowed patients to choose and train their own home care attendants paid for by Medicaid

of access to patients with ventilatory compromise which was to give rise to using positive pressure through a tracheotomy, enhanced by the lack of sufficient negative pressure units, the greater familiarity of anesthesiologists with positive pressure manual ventilation, and the continuing polio epidemics. The use of NPNIV with tracheotomy reduced the mortality from bulbar polio to 2–10 % [86, 87].

As more and more patients began to recover from polio and no longer needed 24/7 respiratory support, Kelleher and coworkers from 1952 to 1954 demonstrated that the use of Monaghan and/or Kifa cuirasses for partial or nocturnal NPNIV support was effective after patients regained adequate awake breathing on their own [88]. There were increasing reports of successes using such nocturnal support for patients with severe skeletal deformities such as post-tuberculous thoracoplasty and kyphoscoliosis [89, 90].

An innovative inhalation therapist, F. H. Terhaar from California, designed a clear plastic shell cuirass ventilator in 1958 which fitted over the lower thorax and abdomen leaving the shoulder girdle free. The Hemo-Dyne Vital Capacitator was manufactured by Dynamic Air Engineering in 1959 in order to compare the circulatory effects of negative pressure from positive pressure ventilation, where the former was found to augment cardiac output whereas the latter decreased it. It was used to treat patients with heart failure [91]. My post polio and fibrothorax patients chronically using nocturnal NPNIV retained third space, diuretic resistant, fluid after general anesthesia for major abdominal cancer surgery when on postoperative positive pressure ventilation. They diuresed after they were replaced on their negative pressure systems, up to 7 L in 24 h [92]. A. Marks et al. using the Emerson made Poncho wrap plastic garment ("Rain Coat") applied through a rigid thoracoabdominal grid cage resting on a rigid plate, designed a novel patient-synchronized system, triggered by the patient from minute pressure changes at the nostrils or from a tracheotomy to initiate a breath. Even though the Poncho wrap could be used in children, the time and labor-intensive process of assuring an adequate seal using multiple clips along with the fitting process and for continuous supervision led to its disuse [93] (Fig. 22a, 22b and 22c).

Studies by several authors from 1951 to 1954, the first of which was Fred Plum and coworkers in 1951, compared the efficacy of cuirasses with tanks by measuring tidal volumes. Tanks were found to generate from 34 to 100 % more volume than cuirasses in ten polio patients. Patients dying using cuirasses were described as having "anterior emphysema [94]." Collier and Affeldt assessed 14 polio patients using a tank, when the tidal volume was taken as 100 % as base, and compared it to the thoracoabdominal cuirass and the chest shell. The patients, as their own controls, received 47 % of the tidal volume that the tank generated from the chest cuirass while the thoracoabdominal cuirass generated 62 % of the tidal volumes that the tank did, at the same negative pressures [95]. Upon increasing the negative pressure to obtain more volume, the pressure on the abdomen from the chest shell restricted diaphragm descent. In 1954 Bryce-Smith and Davis compared the tidal volumes delivered by the tank with the thoracic cuirass and the Rocking Bed in six healthy anesthetized volunteers given curare. To obtain equivalent tidal volumes the cuirass needed much more negative pressure [96]. This was also confirmed by Benton and Kriete in 1957 when they compared the cuirass, Rocking Bed and Pneumobelt and found that all three of these systems provided 50 % less tidal volume than a tank or positive pressure through a tracheotomy [97]. Cardus et al. compared arterial blood gases using three kinds of ventilators [98]. I measured a 30 to 40 % greater tidal volume from patients in the lateral decubitus position on a Rocking Bed than when they were supine, presumably due to unloading the chest and abdominal wall muscles from the hydrostatic pressure from abdominal organs and gravity, allowing both more chest expansion and diaphragmatic descent [71].

A major change in the application NPNIV and positive pressure support came about from the Danish polio epidemic of 1952. Positive pressure had been used by anesthesiologists to administer anesthesia by manually squeezing a bag for intubated patients, for temporary respiratory depression and/or when curare was

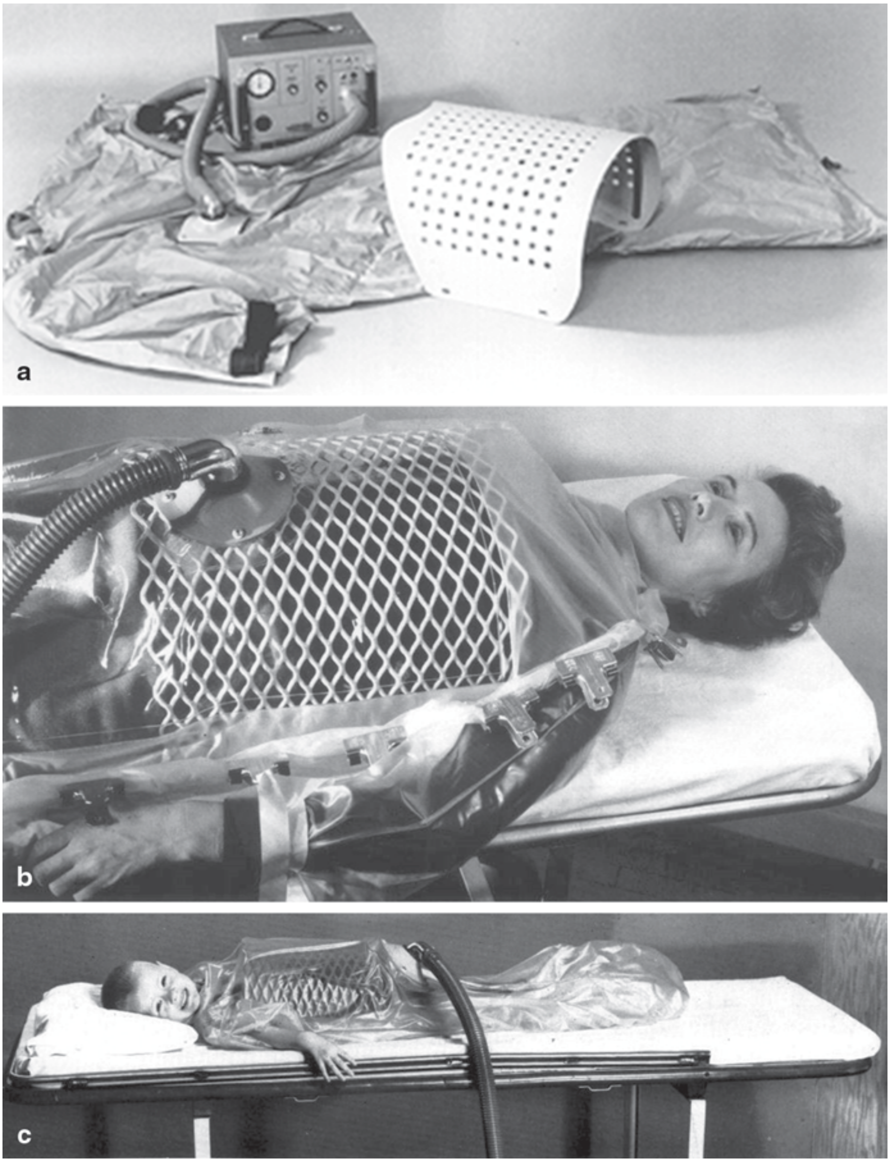

Fig. 2.22 A Emerson Body suit: Full body garment with rigid chest grid. The negative pressure pump, Maxivent, is shown. The back plate is not shown. Used with permission from J. H. Emerson Co. **b** Emerson Plastic “Rain Coat” or Poncho on a model. Note all the clips needed to “seal” the Poncho to allow a vacuum and where the upper third of the chest is compressed with inspiration. Used with permission from J. H. Emerson Co. **c** Use of the Poncho in a child when the adult Poncho encloses the whole patient. (Used with permission from J. H. Emerson Co.)

needed. That year saw 2722 admissions for acute poliomyelitis of which 866 (32 %) were paralytic, of which 316 (nearly 37 %) needed ventilation. For the 70 patients who needed a ventilator at the same time, there was only one tank and six cuirasses. This triggered Dr. H.C. A. Lassen with Dr. B. Ibsen to develop a high tracheotomy through which manual positive pressure could be delivered. Their previous experience in 1934 through 1944 saw a mortality of 80 %, using the cuirass, drop to 40 % by using positive pressure ventilation through a tracheotomy [99]. This experience and the increasing instances of less efficacious cuirass use for some patients led to expanding the use of positive pressure systems with new sets of problems.

It was just a matter of time before physicians saw the potential for use of NPNIV for support in other settings. In 1955, P. Tooker reported his use of a Kifa cuirass to ventilate patients during bronchoscopy and laryngoscopy [100]. Others soon used the Monaghan shell or the Emerson wrap for the same purpose. R. A. Green and D. J.Coleman and others reported on the difficulty of ventilating obese or emphysematous patients using cuirasses [101–104]. Of 248 patients who were cuirass ventilated for elective procedures, 16 could not be adequately ventilated either due to poor fit, obesity or chronic lung disease as reported by G. Wallace et al. in 1961 [105]. Like Helperin, [104] I used a modified poncho successfully for upper airway and GI endoscopy, both upper and lower colonoscopy, for more than 35 patients who were ventilator dependent.

In 1955, E. A. Pask from England suggested that improvement in design of the cuirass would make it more comfortable for long-term use, would deliver better ventilation, and with enough ventilation nursing could be provided in the prone position, allowing greater utility [106]. This triggered E. J. Tunnicliffe in 1958 to produce a jacket made of a blend of cotton with nylon, sealed with straps at the arms, neck, and buttocks over a plastic shell powered by an air pump which was proven to produce more than double the tidal volume of a standard cuirass (Fig. 2.23). J. M. K. Spalding and L. Opiel confirmed this with their report comparing the equivalency for the volume of air delivered with the Tunnicliffe cuirass jacket with IPPB in patients with polio and myasthenia gravis [107]. This was successful for long-term ventilation, reported after a year of customized cuirass use by Kinnear et al. with an 88 % survival rate and reduced need for hospitalization in patients with thoracoplasty and neuromuscular diseases [108].

Despite the availability of customized cuirasses from J. H. Emerson, difficulties with poor fitting, pain and/or calluses at the lateral chest wall or other pressure points from chest wall deformities, and expense led H. H. Pinkerton in 1957 to develop an abdominal cuirass belt made from a large sphygmomanometer-type cuff strapped over the nipples to just below the xiphisternum, and laterally to the posterior axillary line to deliver active positive pressure for exhalation which allowed passive recoil for negative pressure inhalation and ventilatory support. It allowed supported ventilation for airway procedures, a forerunner of the Pneumobelt [109]. Others reported successful Pneumobelt use for ventilatory support for respiratory insufficiency in high quadriplegics [110, 112].

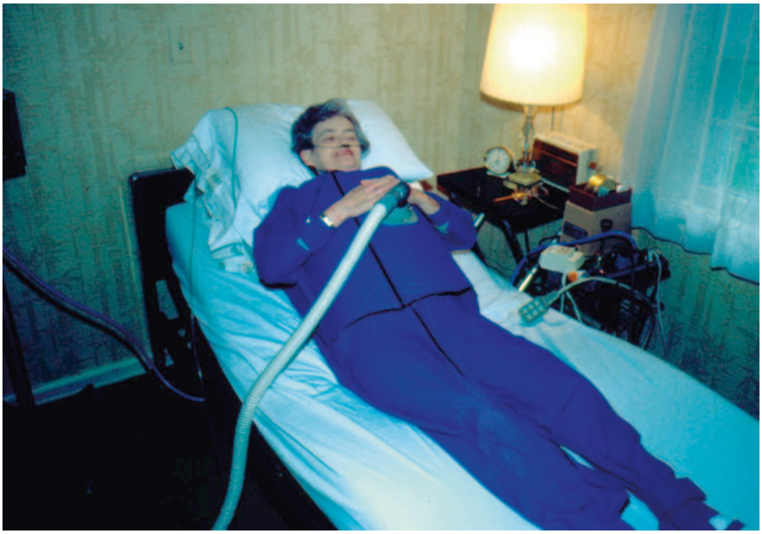

Fig. 2.23 A patient with Gold IV COPD (FEV1 0.3 L and chronic hypercapnic respiratory failure wearing a Nu-Mo suit, easier to place and effectively seal. She is using oxygen by nasal cannula at home. She was supported with negative pressures of −40 cm H_2O nightly for more than 5 years. She experienced more dyspnea relief when she used her nebulizer medications in the suit; her nebulizer is next to her bed. She was able to return to playing the church organ after the use of this system. She was never rehospitalised. *FEV1* forced expiratory volume in the first second

Specific Remarks Regarding Poliomyelitis

The polio epidemic might have been controlled sooner but for politics, limited vision, academic infighting, and personalities. Dr. Hilary Kaprowski was the first to experiment with live polio vaccine in 1948, which he cultivated in the brains of polio susceptible cotton rats. He drank a blenderized portion of the brains, first to inoculate himself and then his children. No ill effects were suffered; no one got polio. He was then asked in 1950 to inoculate 20 mentally disabled children from Letchworth Village, Rockland, New York. Seventeen of the 20 developed antibodies to polio; the other three were already antibody positive prior to inoculation; none suffered any complications nor developed polio [113]. He was asked to provide his oral vaccine to several countries in Europe with similar results. The academic medical community protested his efforts due fear of using live, attenuated virus and to a complex interplay between his outsized personality and politics with science. Thus, an unproved theoretical fear led to the delay of mass vaccination until Dr. Jonas Salk developed an injectable dead virus vaccine in 1955. The immunity lasted only a year for some and some children tragically got polio from a virulent viral contaminated batch, ending the use of the Salk vaccine. Dr. Albert Sabin, who had worked with Hilary Kaprowoski, found that the polio virus invaded through the gut epithelium which led to his development of an effective attenuated oral vaccine in 1960. Wide spread oral vaccination led to the cessation of polio epidemics in industrialized countries [114]. However, polio remains prevalent, episodically, in third world countries where the vaccine is not available due to politics and/or ignorance and fear [115]. The most recent was an outbreak in Syria, in October, 2013, spreading to Lebanon due to the influx of Syrian refugees when vaccination was prevented by migration and lack of safety for health-care workers [116]. Taliban propaganda also halted polio vaccination in Pakistan and Somalia. In September 2013, The Bill and Melinda Gates Foundation received one of the Albert and Mary Lasker Awards for public service for their work in providing the Sabin oral polio vaccine to thousands of children in Afghanistan, Nigeria, and Pakistan, with the goal of eradicating the virus from the earth as was done with smallpox [117].

A Personal History Regarding NPNIV

As the effectiveness of the polio vaccine dramatically reduced the need for NPNIV, there were increasing reports of their application in acute-on-chronic respiratory failure from other causes between 1958 through 1961 in France, as it was considered “more physiological” than IPPB. Oxygen enriched air was added to the use of the thoracoabdominal cuirass with a “slight” positive pressure from a face mask in phase with the cuirass to improve oxygenation [118].

My introduction to negative pressure ventilation came about from a rotation on the Bellevue Hospital’s Chest Service during my residency. An entire building, C & D wings, was dedicated to the care of patients with advanced tuberculosis and the increasing numbers of patients with other chest diseases. With the success of the polio vaccine, no more patients with respiratory paralysis were admitted. The iron lungs had been stored. However, recognition that many more patients with increasing respiratory compromise from other disorders such as post-tuberculous thoracoplasty, pulmonary fibrosis (PF), bronchiectasis, COPD, other neuromuscular disorders (NMD), and kyphoscoliosis (KS) appeared as antibiotic therapy became widely used and allowed recovery from devastating infections, but left persistently symptomatic dyspneic and hypercapnic patients. From the best available recall of physicians from that time, it was Dr. John McClement, the director of the Chest service, with Dr. David Simpson, who began to use the iron lungs for patients with chronic respiratory failure as there were no other effective mechanical ventilators available for longer term use [119]. Only IPPB pressure limited machines, (Bird, Bennett models) were available, and while suitable for delivering nebulized medications, were completely ineffective in providing sufficient longer term ventilation to reverse chronic respiratory failure or relieving intractable dyspnea. It was then that I reasoned that the lungs of these patients were not changed by NPNIV; they were still badly damaged or the chest walls were still noncompliant or the muscles were still too weak. Thus, the ventilatory benefit from the iron lung may be due to their assuming the work of the respiratory muscles, reducing the work of breathing while supporting gas exchange as it relieved dyspnea and thus might “rest” the over burdened respiratory muscles, and that such rest would allow some “recovery.”

Some of the COPD patients had IPPB therapy synchronized with their iron lungs, enhancing nebulizer delivery of medications, and sometimes to augment their minute ventilation when the maximum achievable negative pressures were not enough to support ventilation during an acute exacerbation of the COPD. Patients were noninvasively ventilated with the iron lung on the chest service for many months, as home care for such patients did not exist, until they generally died from pneumonia. This led to my working with Dr. Dudley F. Rochester, who had shown in dogs that the oxygen consumption of the diaphragm at increasing work levels was linearly proportional to the sum of the integrated electrical activity (EMG) of the diaphragm [120, 121]. Applying this concept to humans was studied by placing esophageal electrodes to record diaphragmatic EMGs in normal volunteers and stable, hospitalized patients with diverse causes of chronic hypercapnic respiratory failure. We found in the normal volunteers that diaphragmatic EMG activity could be reduced but not abolished by iron lung ventilation even when the negative pressures caused alveolar hyperventilation to end tidal CO_2 levels of 20 to 30 mmHg. However, it was not until a resistive load, by blocking one nostril, or an elastic load, by binding the chest and abdomen at functional residual capacity were added, that the normal subjects' diaphragmatic EMG was nearly abolished, with no awareness nor discomfort, just as Drinker described in himself. The patients with COPD, KS, and NMD were all easily "captured" by the second to third cycle after turning on the iron lung ventilator; [122] we observed that as soon as the iron lung ventilator was turned on the patient's use of accessory muscles and nasal flaring ceased, and the patient no longer felt air hunger. The relief of dyspnea coincided with the loss of the EMG activity when ventilation was fully supported. This occurred even when changing the pressures to allow the $PaCO_2$ level to rise, stay the same, or fall, indicating that the mechanism was not due to acutely altering the CO_2 level. Oxygen saturations were kept constant with the same or lower level of oxygen supplementation. EMG activity was regularly increased by the use of a mouth piece and by IPPB therapy. Thus, the dyspnea relief stemmed from the assumption of work by the NPNIV and not due to a change of the CO_2. When patients were allowed to choose the pressure level for breathing satisfaction, which I call "Respiratory Satiety," they all chose higher ventilation levels that would lower their $PaCO_2$, for example, to levels below 34 mmHg in the neuromuscular patients. This fostered the use of negative pressure ventilation for sleep for these patients in their homes, anticipating that such support might allow for improved ventilatory efficiency and function and less dyspnea during the day, better sleep at night, and a better quality of life. Many gained weight with improved appetites. Body composition analysis showed it was mostly muscle and some fat but not water. This led to preliminary studies which showed that "nocturnal" noninvasive ventilation at the patient's chosen level of support reduced the work of breathing enough to enhance appetite and food intake, possibly also due to better nutrient absorption with the reduction in right-sided pressures on mesenteric blood flow and/or better appetite as gas exchange improved and sleep was now possible [71]. The better sleep stimulated me to help establish a Sleep Laboratory in 1976 so that this efficacy could be better studied. Since then the neurobiology of sleep has become a whole new discipline affecting many spheres of the lives of normal people and those with cardiopulmonary, neurological, obesity-related, and neuropsychiatric disorders. More than 100 of my patients have used NPNIV at home successfully for from 2 to 40 plus years. One such 6 foot 5 inch man would roll his iron lung into the hospital for use when he developed a new medical problem as the nearest hospital did not have such a unit and he refused to be intubated [71]. This stimulated me to design a more patient friendly, easier to apply unit, a garment, Pneumosuit or Nu-Mo suit, made from breathable, machine washable Gortex fabric, (used for garments for Astronauts) into an adult pajama-like suit with a full length sealing zipper, used with the Emerson grid cage on a back plate, adding a cushion for greater comfort on the back plate, and vacuum pump. The grid chosen was one that covered the thorax from the clavicles to at least mid-abdomen or to just above the symphysis pubis. A larger grid could accommodate patients with severe chest wall deformities with additional padding at pressure points for comfort. With the availability of Velcro it was much easier to make individually adjustable airtight seals at the neck, wrists and ankles (Fig. 2.23). An optional Velcro opening in the lower back would allow toileting without the removing the suit. The gentle compression "massage" of the arms and legs by the negative intrasuit pressure enhanced venous return and increased the oxygen saturation or PaO_2 without an increase in nasal oxygen supplementation, reflecting a better distribution of blood flow to the better expanded lungs, and thus improving ventilation–perfusion matching. This suit was made by a parishioner in the church of a minster whose wife had end-stage hypercapnic COPD with right heart failure, and who had successfully used the Emerson Poncho in the hospital. The cumbersome, time consuming multi-clip closure system from the plastic Emerson Poncho "Rain Coat" was replaced by the Nu-Mo suit. Available in several sizes including for children, it was distributed by the New York Emerson Company and Life Care company representatives who supplied it to anyone who requested it. The negative pressures needed to adequately ventilate were in the range of −20 to −45 cm H_2O, while often higher than the pressures needed for younger polio and/or other neuromuscular patients without chest cage deformity, it was needed for those with very stiff chest walls, increasing with age [123].

Elective diagnostic procedures have now been safely/successfully performed using NPNIV in the Nu-Mo suit or cuirass jacket for endoscopies including laryngoscopy, bronchoscopy, and esophagogastroscopy. For colonoscopy and cystoscopy, the suit was cinched just above the symphysis pubis with a Velcro belt allowing for diagnostic evaluation and intervention for such compromised patients [124].

After presenting data at an Aspen lung conference [125], several different groups at different institutions tried using NPNIV in trials for patients with COPD with variable results. In two randomized prospective trials; both in ambulatory patients with COPD, one from McGill University [126] and one from Boston [127] to determine if respiratory muscle rest could be achieved with improved function using NPNIV, there was no difference between the sham and actually treated patients. These patients were not all as dyspneic and the pressures used were not individualized for satiety of dyspnea. Based on these findings as well as poor adherence to therapy, the trial was terminated and NPNIV was not recommended. However, Feranadez et al. confirmed our report with a shorter duration of 8 h of NINPV 2 days in a row [128]. The studies showing no effect differed from ours, even though nonrandomized, as few of their patients had revolving door hospitalizations without recurring infections as the cause for their COPD exacerbations or were as hypercapnic (>54 mmHg CO2) as all of our 18 patients. Fourteen of these used the Nu-Mo suit NPNIV, where settings were individualized till "Respiratory Satiety" was achieved in-hospital before discharge to home. The other four were treated with NPPV with oral or nasal masks due to developing upper airway obstruction with NPNIV. After 5 months of nocturnal home ventilator support all had improved pulmonary function, respiratory maximum static pressures, and awake gas exchange [129]. Despite now being classified as having Gold Stage IV COPD, all were domiciled and none were readmitted to the hospital for more than 3 years.

The Italian physicians, Antonio Corrado and others continue to apply NPNIV for acute, acute-on-chronic and chronic respiratory failure, using an iron lung of their own design. Their goal has been to provide ventilatory support without endotracheal intubation. They were successful in 77% of 258 consecutive patients with acute respiratory failure, of which 40% were supported with NPNIV. The complication rates from NPNIV stemmed from upper airway obstruction during use, the most frequent (16%), claustrophobia (11.4%), back pain (5%), GI bleeding (2%), and gastric insufflation (1.3%) in one patient who contracted pneumonia (0.6%) [130]. Raymondos et al. compared the hemodynamic consequences in 46 intubated patients with Acute Respiratory Distress Syndrome (ARDS) from diverse causes using continuous negative NPNIV versus continuous positive pressure noninvasive ventilation in the same patients. They found lower transpulmonary and intra-abdominal pressures, and improved hemodynamics, with NPNIV [131]. There was 50% mortality, all in those whose ARDS stemming from aspiration. In 2012, Engelberts et al. reported in mice that when waveforms and lung volume history are matched, positive and negative pressure ventilation, both ex vivo and in vivo, are biologically indistinguishable [132].

The most recent innovation in NPNIV is the biphasic cuirass ventilator (BPCV) of Hayek, an Israeli physician who designed a chest shell unit with an electronic digital circuit with both negative and positive pressure options over a wide range of rates and pressures, which can both be individually set for "best support" dictated by individual circumstances. He proposed that the BPCV be used for wounded soldiers, during anesthesia for diagnostic and otolaryngogical procedures, in neurosurgical trauma patients, for acute respiratory failure in COPD patients, in children, for support during weaning from positive pressure ventilation of intubated patients, in patients with neuromuscular disorders, and patients with central alveolar hypoventilation syndromes. It has an external high frequency oscillator option for the mobilization of secretions which has been reported to be effective [71, 133–141]. A 27-year-old male artist patient of mine has rare lymphatic tumors, disfiguring and causing pain in multiple bones, including most of the right rib cage, from which many surgical extirpations (one per year from age 7 weeks) and rod placement for severe scoliosis of his spine have been done, resulting in an extremely rigid, deformed thorax with no functional right lung. This left him ventilator dependent

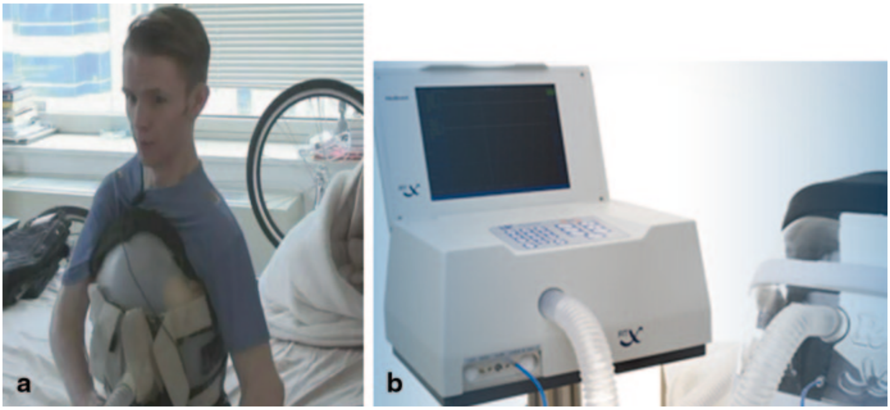

Fig. 2.24 A Hayek biphasic cuirass ventilator (*BPCV*) and customized chest shell being used by a 27-year-old patient with a severely deformed and noncompliant rib cage and one functioning lung with bronchiectasis and chronic hypercapnic respiratory failure. Successful use allowed tracheotomy removal and a return to school and work. B Hayek biphasic ventilator pump unit at bedside. The unit is not yet portable. It has a high frequency oscillating feature, allowing use for secretions mobilization

through a tracheotomy. His frequent debilitating pneumonias with hemoptysis and bouts of recurring tracheitis with the development of bronchiectasis in the functioning left lower lobe prompted him to try the Hayek biphasic cuirass for sleep, and for rest after physical therapy sessions. He needed negative pressures of −40 to −45 cm H_2O. He now has been successfully decannulated and has gone back to school while he pursues his livelihood in art [142] (Fig. 2.24a and 2.24b).

As critical care units expanded across the country when intubation became a more rapid, effective means for ventilating acutely failing patients, use, experience with, and availability of NPNIV units diminished. There has been resurgence of interest in NPNIV, especially in Italy, as the complications of positive pressure ventilation from intubation and tracheotomy have continued to rise as sicker and older patients with more comorbidities are resuscitated [143]. However, all the companies making or supplying negative pressure systems have been sold, and no longer supply such equipments in the USA. Not being able to obtain replacements for worn out shells, or Porta-Lungs, or Nu-Mo suits or their pumps, patients still supported with NPNIV are having to have them custom made by orthothic specialists willing to do so, often not covered by insurance. Since these patients are functioning, secure, and surviving for over 60 years with NPNIV, they are loath to use positive pressure devices.

Other novel noninvasive support systems exist, as discussed above, such as the Rocking Bed, introduced in 1932 [142–144], a gravity motion bed, where gravity is used to move the paralyzed diaphragm passively to effect air flow (Fig. 2.25), and the Pneumobelt, where positive pressure is cyclically applied through an inflatable wide belt or with a balloon inserted into a corset for compressing the abdomen for “active” exhalation and “passive” recoil inhalation [145] (Fig. 2.26). Both were

Fig. 2.25 The Emerson Rocking Bed: Feet down −45°: diaphragms descend and chest wall moves outward from gravity for passive inspiration. Head down −15°: for exhalation when the abdominal contents are moved up against the passive diaphragms into the chest and the chest wall recoils. The degrees of motion could be individually adjusted. This bed was used for post-polio patients for greater than 45 years, and for patients with post-open heart surgery diaphragm paralysis until recovery ensued

Fig. 2.26 Patient with Duchenne's muscular dystrophy in his customized wheelchair using a Pneumobelt during the day and negative pressure suit night. The pump uses the same battery that powers his chair which is placed on a shelf on his wheelchair behind him, making him mobile

successfully used for many years during the polio epidemic era as noted. In 1989, Abd and Braun et al. reported of 1225 patients having open heart coronary by-pass and/or valve surgery over an 18-month period from one institution, the use of the Rocking Bed in 13 unweanable patients, due to phrenic nerve injury during open heart surgery, allowed them to be extubated after 1–2 days, and discharged home where they used the beds until recovery ensued from 4 to 27 months after [58]. The Rocking Bed is no longer available, and patients who prefer to continue use of the Pneumobelt have been driven to making customized units on their own [146].

With the advent of better noninvasive, smaller, portable positive pressure units and greater choice of more acceptable, comfortable interfaces for NPPV, the evolution of knowledge about sleep respiratory disorders, and the complications of lung injury and infections from endotracheal/tracheotomy supported ventilation, noninvasive positive pressure modalities are being increasingly used to support infants through all ages for all causes of respiratory insufficiency and failure. Patients with central apneas and severe facial deformities can still be supported with NPNIV. Engineering system developments with digital technology and wider recognition and diagnoses of many disorders of ventilation, both acute and chronic, with the view to lessen complications from invasive ventilator support, are continuing to evolve. Flexibility of options with knowledge, dedication, experience, and patient preferences can make NPNIV a still useful modality for patients, as in Italy.

Summary Many brilliant scientists, physicians, and engineers have made keen, ingenious observations, contributed knowledge, evolved physiological principles through experimentation in animals and man, developed innovative ideas, and have offered an astounding and intriguing number of designs, from positive pressure, to negative pressure, to combined modalities and then back to positive pressure support, while finding new applications of ventilator support for inadequate or absent ventilation from a host of causes since pre-Biblical times. Many were impractical or useless and failed, but their failures fostered new efforts and designs, demanded by events, notably, drowning or asphyxiations, from pre-Biblical times, increasing in the seventeenth through the nineteenth centuries, and the polio epidemic in the twentieth century. Financial support, first from industry, then from private and government sources, permitted research to foster understanding and to developing and manufacturing workable systems for widespread application. The wealth of knowledge and experience gained led to the saving of many lives. These efforts through the ages takes us to the current day, bringing together the data to serve as a basis for improving the care of the ever increasing numbers of patients who might still benefit from using negative pressure noninvasive ventilation for a variety of respiratory disorders awake, in sleep, or both, and for potentially extended periods of time, up to a lifetime for some.

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