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Understanding Mechanical Ventilation

A Practical Handbook

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Second Edition

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'To my parents'

Preface to the Second Edition

Simplify, simplify!

Henry David Thoreau

For writers of technical books, there can be no better piece of advice.

Around the time of writing the first edition – about a decade ago – there were very few monographs on this subject: today, there are possibly no less than 20.

Based on critical inputs, this edition stands thoroughly revamped. New chapters on ventilator waveforms, airway humidification, and aerosol therapy in the ICU now find a place. Novel software-based modes of ventilation have been included. Ventilator-associated pneumonia has been separated into a new chapter. Many new diagrams and algorithms have been added.

As in the previous edition, considerable energy has been spent in presenting the material in a reader-friendly, conversational style. And as before, the book remains firmly rooted in physiology.

My thanks are due to Madhu Reddy, Director of Universities Press – formerly a professional associate and now a friend, P. Sudhir, my tireless Pulmonary Function Lab technician who found the time to type the bits and pieces of this manuscript in between patients, A. Sobha for superbly organizing my time, Grant Weston and Cate Rogers at Springer, London, Balasaraswathi Jayakumar at Spi, India for her tremendous support, and to Dr. C. Eshwar Prasad, who, for his words of advice, I should have thanked years ago.

Above all, I thank my wife and daughters, for understanding.

Hyderabad, India Ashfaq Hasan

Preface to the First Edition

In spite of technological advancements, it is generally agreed upon that mechanical ventilation is as yet not an exact science: therefore, it must still be something of an art. The science behind the art of ventilation, however, has undergone a revolution of sorts, with major conceptual shifts having occurred in the last couple of decades.

The care of patients with multiple life-threatening problems is nothing short of a monumental challenge and only an envied few are equal to it. Burgeoning information has deluged the generalist and placed increasing reliance on the specialist, sometimes with loss of focus in a clinical situation. Predictably, this has led to the evolution of a team approach, but, for the novice in critical care, beginning the journey at the confluence of the various streams of medicine makes for a tempestuous voyage. Compounding the problem is the fact that monographs on specialized areas such as mechanical ventilation are often hard to come by. The beginner has often to sail, as it were, "an uncharted sea," going mostly by what he hears and sees around him.

It is the intent of this book to familiarize not only physicians, but also nurses and respiratory technologists with the concepts that underlie mechanical ventilation. A conscious attempt has been made to stay in touch with medical physiology throughout this book, in order to specifically address the hows and whys of mechanical ventilation. At the same time, this book incorporates currently accepted strategies for the mechanical ventilation of patients with specific disorders; this should be of some value to specialists practicing in their respective ICUs. The graphs presented in this book are representative and are not drawn to scale.

This book began where the writing of another was suspended. What was intended to be a short chapter in a handbook of respiratory diseases outgrew its confines and expanded to the proportions of a book.

No enterprise, however modest, can be successful without the support of friends and well wishers, who in this case are too numerous to mention individually. I thank my wife for her unflinching support and patience and my daughters for showing maturity and understanding beyond their years; in many respects, I have taken a long time to write this book. I also acknowledge Mr. Samuel Alfred for his excellent secretarial assistance and my colleagues, residents, and respiratory therapists for striving tirelessly, selflessly, and sometimes thanklessly to mitigate the suffering of others.

Ashfaq Hasan, 2003

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Chapter 1
Historical Aspects of Mechanical Ventilation

As early as in the fifth century BC, Hippocrates, described a technique for the prevention of asphyxiation. In his work, "Treatise on Air," Hippocrates stated, "One should introduce a cannula into the trachea along the jawbone so that air can be drawn into the lungs." Hippocrates thus provided the first description of endotracheal intubation (ET).[4,10]

The first form of mechanical ventilator can probably be credited to Paracelsus, who in 1530 used fire-bellows fitted with a tube to pump air into the patient's mouth. In 1653, Andreas Vesalius recognized that artificial respiration could be administered by tracheotomising a dog.[24] In his classic, "De Humani Corporis Fabricia," Vesalius stated, "But that life may … be restored to the animal, an opening must be attempted in the trunk of the trachea, in which a tube of reed or cane should be put; you will then blow into this so that the lung may rise again and the animal take in air… And also as I do this, and take care that the lung is inflated in intervals, the motion of the heart and arteries does not stop…."

A hundred years later, Robert Hooke duplicated Vesalius' experiments on a thoracotomised dog, and while insufflating air into an opening made into the animal's trachea, observed that "the dog… capable of being kept alive by the reciprocal blowing up of his lungs with Bellows, and they suffered to subside, for the space of an hour or more, after his Thorax had been so displayed, and his Aspera arteria cut off just below the Epiglottis and bound upon the nose of the Bellows."[11] Hooke also made the important observation that it was not merely

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the regular movement of the thorax that prevented asphyxia, but the maintenance of phasic airflow into the lungs. What was possibly the first successful instance of human resuscitation by mouth-to-mouth breathing was described in 1744 by John Fothergill in England.

The use of bellows to resuscitate victims of near-drowning was described by the Royal Humane Society in the eighteenth century.[20] The society, also known as the "Society for the Rescue of Drowned Persons" was constituted in 1767, but the development of fatal pneumothoraces produced by vigorous attempts at resuscitation led to subsequent abandonment of such techniques. John Hunter's innovative double-bellows system (one bellow for blowing in fresh air, and another for drawing out the contaminated air) was adapted by the Society in 1782, and introduced a new concept into ventilatory care.

In 1880, the endotracheal route was used, possibly for the first time, for cannulation of the trachea, and emerged as a realistic alternative to tracheotomy.[14] Appreciation of the fact that life could be sustained by supporting the function of the lungs (and indeed the circulation) by external means led to the development of machines devised for this purpose. In 1838, Scottish physician John Dalziez described the first tank ventilator. In 1864 a body-tank ventilator was developed by Alfred Jones of Kentucky.[9] The patient was seated inside an air-tight box which enclosed his body, neck downwards. Negative pressure generated within the apparatus produced inspiration, and expiration was aided by the cyclical generation of positive pressure at the end of each inspiratory breath. Jones took out a patent on his device which claimed that it could cure not only paralysis, neuralgia, asthma and bronchitis, but also rheumatism, dyspepsia, seminal weakness and deafness. Woillez's hand-cranked "spirophore" (1876) and Egon Braun's small wooden tank for the resuscitation of asphyxiated children followed. The former, the doctor operated by cranking a handle; the latter needed the treating physician to vigorously suck and blow into a tube attached to the box that enclosed the patient. In respect of Wilhelm Shwake's pneumatic chamber, the patient himself could lend a hand by pulling and pushing against the bellows.

In 1929, Philip Drinker, Louis Shaw, and Charles McKhann at the Department of Ventilation, Illumination, and Physiology, of the Harvard Medical School introduced what they termed "an apparatus for the prolonged administration of artificial respiration."[9] This team which included an engineer (Drinker), a physiologist (Shaw), and a physician (McKhann) saw the development of what was dubbed "the iron lung." Drinker's ventilator relied on the application of negative pressure to expand the chest, in a manner similar to Alfred Jones' ventilator. The subject (at first a paralyzed cat, and then usually a patient of poliomyelitis) was laid within an air-tight iron tank. A padded collar around the patient's neck provided a seal, and the pressure within the tank was rhythmically lowered by pumps or bellows. Access to the patient for nursing was understandably limited, though ports were provided for auscultation and monitoring.* Emerson, in 1931 in a variation upon this theme incorporated an apparatus with which it was possible to additionally deliver positive pressure breaths at the mouth; this made nursing easier. The patient could now be supported on positive pressure breaths alone, while the tank was opened periodically for nursing and examination.

Toward the end of the nineteenth century, a ventilator functioning on a similar principle as the iron tank was independently developed by Ignaz von Hauke of Austria, Rudolf Eisenmenger of Vienna, and Alexander Graham Bell of the USA. Named so because of its similarity to the fifteenth century body armor, the "Cuirass" consisted of a breast plate and a back plate secured together to form an air-tight seal. Again, negative pressure generated by means of bellows (and during subsequent years, by a motor from a vacuum cleaner) provided the negative pressure to repetitively expand the thoracic cage and so move air in and out of the lungs. The Cuirass, by leaving the patient's arms unencumbered, and by

*A rich American financier's son who developed poliomyelitis during a visit to China was transported back home in a Drinker-tank by a dozen caregivers which included seven Chinese nurses. He used the iron lung for more than two decades during which he married and fathered three children.

causing less circulatory embarrassment, offered certain advantages over the tank respirator; in fact, Eisenmenger's Cuirass was as much used for circulatory assistance during resuscitation as it was for artificial ventilation. Despite its advantages, the Cuirass proved to be somewhat less efficient than the tank respirator in providing mechanical assistance to breathing.

During the earliest years of the twentieth century, advances in the field of thoracic surgery saw the design of a surgical chamber by Ferdinand Sauerbruch in 1904. This chamber functioned much on the same lines as the tank respirator except that the chamber included not only the patient's torso, but the surgeon himself.[4] Brauer reversed Sauerbruch's principle of ventilation by enclosing only the patient's head within a much smaller chamber which provided a positive pressure. In 1911, Drager designed his "Pulmotor," a resuscitation unit which provided positive pressure inflation to the patient by means of a mask held upon the face. A tilted head position along with cricoid pressure (to prevent gastric insufflation of air) aided ventilation. The unit was powered by a compressed gas cylinder, and used by the fire and police departments for the resuscitation of victims.[18]

Negative pressure ventilators were extensively used during the polio epidemic that ravaged Los Angeles in 1948 and Scandinavia in 1952. During the Scandinavian epidemic, nearly three thousand polio-affected patients were treated in the Community Diseases Hospital of Copenhagen over a period of less than 6 months.[16] The catastrophic mortality during the early days of the epidemic saw the use of the cuffed tracheostomy tube for the first time, in patients outside operating theaters. The polio epidemics in USA and Denmark saw the development and refinement of many of the principles of positive pressure ventilation.

In 1950, responding to a need for better ventilators, Ray Bennet and colleagues developed an accessory attachment with which it became possible to intermittently administer positive pressure breaths in synchrony with the negative pressure breaths, delivered by a tank ventilator.[3] The supplementation of negative pressure ventilation with intermittent positive pressure breaths did result in a substantial reduction in mortality.[9,12,13] Bennet's valve had originally been designed to enable pilots to breathe comfortably at high altitudes. The end of the Second World War saw the adaptation of the Bennet valve to regulate the flow of gases within mechanical ventilators.[17] Likewise, Forrest Bird's aviation experiences led to the design of the Bird Mark seven ventilator.

Around this time, interest predictably focused on the physiological effects of mechanical ventilation. Courmand and then Maloney and Whittenberger made important observations on the hemodynamic effects of mechanical ventilation.[15,17] By the mid 1950s, the concept of controlled mechanical ventilation had emerged. Engstrom's paper, published in 1963, expostulated upon the clinical effects of prolonged controlled ventilation.[7] In this landmark report, Engstrom stressed on the "complete substitution of the spontaneous ventilation of the patient by taking over both the ventilatory work and the control of the adequacy of ventilation" and so brought into definition, the concept of CMV. Engstrom developed ventilator models in which the minute volume requirements of the patient could be set. Setting the respiratory rate within a given minute ventilation determined the backup tidal volumes, and the overall effect was remarkably similar to the IMV mode in vogue today.

Improvements in the design of the Bennet ventilators saw the emergence of the familiar Puritan-Bennet machines. The popularity of the Bennet and Bird ventilators in USA (both of which were pressure cycled) soon came to be rivaled by the development of volume-cycled piston-driven ventilators. These volume preset Emerson ventilators better guaranteed tidal volumes, and became recognized as potential anesthesia machines, as well as respiratory devices for long-term ventilatory support.

Toward the end of the 1960s, with increasing challenges being presented during the treatment of critically ill patients on artificial ventilation, there arose a need for specialized areas for superior supportive care. During this period, a new disease entity came to be recognized, the Adult Respiratory Distress Syndrome, or the acute respiratory distress syndrome