History of Technology in the Intensive Care Unit

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THE HISTORY OF INVASIVE MONITORING

Early Invasive Monitoring

Invasive monitoring in the intensive care unit owes a great deal to many forward-thinking pioneers in this field. In 1929, the German resident Forssmann, in an attempt to deliver drugs more effectively for cardiac resuscitation, inserted a nonflow directed (no balloon) catheter into his own arm and advanced it to what was calculated to be his right heart (Fig. 1). He walked to the radiology department to verify its placement by radiography.1 Forssmann’s successful experiment was considered a stunt by the German medical community and he was forced to change his career to urology. Ultimately, he was recognized for his contribution to the development of cardiac catheterization with a Nobel Prize in science in 1956.1 The next two decades saw the creation of cardiac catheterization laboratories to investigate and treat congenital, rheumatic, and eventually ischemic heart disease. In the 1960s, the only physiologic tool available for bedside evaluation was the central venous pressure (CVP) measurement as first described by Wilson.2 The limitations of CVP monitoring were becoming evident over the first decade of its use in clinical practice.3

During this same time Myocardial Infarction Research Units (MIRU) and Shock Research Units (SRU) demonstrated the value of hemodynamic measurements in acutely ill patients with both cardiogenic and other forms of shock.4,5 Del Guercio and colleagues6 applied similar techniques for surgical patients. However, for measurement of cardiac output, investigators had to rely on indocyanine green dye dilution techniques. Indocyanine green dye had to be injected into the right atrium

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and a sensor detected the dye in the radial or femoral artery. The cardiac output was calculated from a curve that could be recorded on paper. Cardiac dilution curves in turn were both tedious and specialized enough to be available to a select few clinicians. Bedside procedures in the early 1970s were also improved by the percutaneous cannulation of central veins and arteries using the modified Seldinger techniques in the intensive care units. Along with the miniaturization and development of disposable pressure transducer systems, new intravascular catheters were becoming available. Thus the stage was set for an explosive growth in the art and science of critical care medicine.

**Pulmonary Artery Catheter**

Right heart catheterization at the bedside has helped enormously in our understanding of critical illness. Swan’s lyrical description of his epiphany while watching sailboats in the Santa Monica Bay that led him to develop the flow directed catheters is well ingrained in critical care lore. However, credit must also go to Lategola and Bradley for the first descriptions of a flow-directed pulmonary artery catheter (PAC) placement. Swan and Ganz ushered in the era of bedside hemodynamic monitoring in the critically ill patients using the flow-directed catheter to enable noncardiologists to perform bedside hemodynamic monitoring, which contributed to the popularity and usefulness of the technique. Cardiac anesthesiology flourished because of the PAC and afterload reduction became a common practice in both the operating room and ICU.

However, there was ongoing controversy about the utility of monitoring pulmonary artery pressures. The classic opinion article of Eugene Robins divided the scientific community into proponents and opponents of Swan-Ganz catheter. The acceptance and widespread use of the expensive and invasive monitoring technique rankled the skeptics. Proponents argued that the PAC was a diagnostic not a therapeutic device. The performance of the procedure by inexpert physicians and the lack of interpretive skills amongst physicians were cited by the enthusiasts. Connors, who previously had produced an article citing the usefulness of PAC over clinical skills,
now authored the widely disseminated study to understand prognosis and preferences and risk of treatment (SUPPORT) study that cast doubt about the life-saving potential of the technique. His article showed a correlation between use of the PAC and mortality. Animated discussion followed in forums of scientific meetings and in the medical literature. Critics of the article noted that it was not designed as a trial of PAC and the propensity score used to create statistical equivalence in the compared groups had limitations. In an editorial response to this study, Bone and Dalen called for a moratorium on the use of the PAC.15

A consensus conference grading the evidence supporting the use of the PAC in different clinical situations was convened.16 The consensus statement disagreed with a moratorium, but it did advocate for further educating physicians about how to place the catheters and the use of data that the catheters provided. One outcome of the consensus process was the creation of the American College of Chest Physicians online Pulmonary Artery Catheter Education Program started in 2001.17 The consensus group further advocated prospective, randomized clinical trials using the PAC to determine its effect on morbidity and mortality in multiple conditions. Prospective clinical trials about the PAC continue to be equivocal.18,19 Even though the decline in the use of the catheters is well documented, a case can be made for invasive hemodynamic monitoring in persistently unstable patients.18,20

The PA catheter likely jump-started the field of critical care medicine by offering insight into patient hemodynamics at the bedside. The questions about its utility and safety as well as new technology have a led to a significant decline in its use. However, it remains an important tool for intensivists and standardized educational programs now exist to help ensure the proper use of the catheter. PAC-derived hemodynamic profiles and the required interpretation continue to be commonplace on critical care board examinations.

ECHOCARDIOGRAPHY

The Early Years

The origins of clinical echocardiography date back to the 1950s under the leadership of Edler and Hertz. Echocardiography was initially performed in the motion-mode, which provided a one-dimensional axial view of the heart displayed as monochromatic dots.21 The technology progressed in the early 1970s with primitive two-dimensional (2D) imaging obtained by recording the various levels of brightness from ultrasonic reflections of the heart. Clinicians were able to visualize cardiac structures and subsequently Doppler was first integrated into echocardiography using Bernoulli’s equation to calculate hemodynamic data as a marker of severity of valvular stenosis.22 Linear array probes, flat probes that provided square images of superficial structures, allowed real time imaging in the 1970s. However, these probes had limited echocardiographic utility because of rib shadows. Subsequently, the development of phased array scanners (ie, flat probes that provided images based on timing of ultrasonic reflections) moved the field forward in the mid-1970s; this advancement allowed for high quality real time imaging of the heart.21 Color flow Doppler was developed in the 1980s and it gave clinicians knowledge about the direction of blood flow.22 These advances allowed the use of echocardiography in critically ill patients to calculate stroke volume and cardiac output.23–25 In 1984, echocardiography was shown to correlate with radionuclide cinematography findings of reversible myocardial depression in patients with septic shock.26,27 However, echocardiography continued to have limited clinical utility in the critically ill, being mainly used for the diagnosis of cardiac tamponade, aortic dissection, and the complications of myocardial infarctions.25
Advances in the technology and the controversies surrounding right heart catheterization led to an explosive growth of echocardiography in critically ill patients in the 1990s. Perhaps its greatest utility is its bedside application in a patient with shock of unknown etiology.

**Expanding Indications**

In 1994, Jardin and colleagues\textsuperscript{28} published a study where he used transthoracic echocardiography (TTE) to show that right heart catheterization (RHC) does not reliably estimate left ventricular end diastolic pressure (LVEDP) in comparison to TTE in patients with septic shock. The development of flexible endoscopes, multiplane views, and the miniaturization of transducers made echocardiography a more viable option to be used in the ICU setting.\textsuperscript{29,30} The refinement of transesophageal echocardiography (TEE), first described by Frazin and colleagues\textsuperscript{31} in the 1970s, increased its clinical utility in the critically ill. TEE was demonstrated to directly change management decisions in 20% of critically ill patients in one study, where the imaging showed an immediate need for pericardiocentesis or a surgical procedure.\textsuperscript{32} Viellard-Baron (a colleague of Jardin) and his colleagues\textsuperscript{33} described his group’s use of TEE in mechanically ventilated patients who were in shock and their institution’s replacement of right heart catheterization by echocardiography to monitor serial hemodynamics. Echocardiography measurement of inferior vena cava diameter changes has been shown to be an indicator of volume status of patients with shock. In echocardiography-based ICU care, these measurements can guide volume resuscitation.\textsuperscript{25} The use of the echocardiogram has helped us to further define critical care disease states. Jardin and colleagues\textsuperscript{34,35} challenged the concept of left ventricular end-diastolic dilatation in early septic shock and showed that more than 30% of patients have hypodynamic shock. Echocardiography has been used to calculate the LVEDP in patients with mitral valve disease, a well-known condition in which the measurement with PA catheter can be inaccurate.\textsuperscript{36} The accepted limitation of right heart catheterization pressure measurements and physical examination for estimating left heart pressures have been a stimulus for echocardiography as a better estimation tool.

**Summary**

Echocardiography is still evolving as a tool in the care of critically ill patients. In some institutions, intensivists have used it to replace the PA catheter as the primary modality for monitoring hemodynamics to determine management decisions. Its use in shock of unknown etiology can help narrow clinicians differential diagnosis.\textsuperscript{37} The addition of postgraduate courses on ultrasound for intensivists at United States' critical care meetings is a recent but positive development.

**RENAL REPLACEMENT THERAPY**

**Brief History of Dialysis**

Since the eighteenth century, physicians have been aware that the peritoneum could be used as a conduit to remove excess and potentially “toxic” fluid from the peritoneal space. Peritoneal dialysis first clinical application was in Germany in 1923 by George Ganter.\textsuperscript{38} He was concerned about the attempts of others to use extracorporeal membranes to dialyze patients that required the use of hirudin, an extract from leeches to provide anticoagulation. He instilled a sterile solution into the peritoneum of a woman with acute renal failure and let it dwell for multiple hours until her electrolytes had corrected. The patient subsequently died when she was discharged from the hospital, which caused Ganter to realize she needed continued therapy.\textsuperscript{38}
During this same era, Georg Haas performed the first intermittent dialysis on a human being when he cannulated the radial artery and antecubital vein and cleansed approximately 150 cc of blood in 15 minutes. The further progression of dialysis was buoyed by the replacement of hirudin with heparin for anticoagulation and the transition from collodion to cellophane for dialysate membrane. Hirudin was associated with significant histamine release in patients resulting in substantial morbidity. Collodion tubing was delicate and was difficult to reuse. Cellophane by comparison was not as fragile and easily sterilized, therefore reusable. These advancements allowed Koff in 1943 to dialyze a woman with malignant hypertension and treat both her renal failure and hypertension. In 1945, he was able to save a woman’s life with acute renal failure, which was the first time a patient lived because of dialysis. Both intermittent and peritoneal dialysis have made significant technological advances since their origins and are now used routinely in the critically ill patient with renal failure.

**Renal Replacement Therapy in ICU**

The incidence of renal failure in critically ill patients is difficult to precisely quantify because of the multitude of definitions used in the past for renal failure and the heterogeneous nature of the disease. One multinational observation study reported that 6% of critically ill patients have acute renal failure and 70% of these patients required renal replacement therapy. Traditional dialysis techniques, such as intermittent hemodialysis and peritoneal dialysis, have potential limitations in critically ill patients. Intermittent hemodialysis exposes ICU patients to severe hypotension in 20%–30% of cases and peritoneal dialysis inadequately clears solutes from the blood. The exposure to hypotension and concern for its deleterious effect as to worsening of renal function was a major impetus for the development of continuous renal replacement therapy (CRRT). Kramer provided the first continuous dialysis option when he created continuous arteriovenous hemofiltration (CAVH) by accessing the femoral artery in 1977. The method was broadly accepted in the United States after Lauer and colleagues published their successful use of CAVH in critically ill patients in 1983. CAVH was an advancement, but its reliance on the patient’s blood pressure to remove fluid and the morbidity associated with cannulating the femoral artery provided the rationale for developing other techniques. After the invention of CAVH, the next two major developments in continuous renal replacement therapy were the introduction of double lumen catheters and peristaltic pumps. The double lumen catheters avoided the need for arterial puncture and the peristaltic pumps made it easier to take off larger volumes of fluid. These developments and the use of countercurrent diasylate comprise the continuous veno-venous hemofiltration (CVVH) system that is used in today’s ICU.

**Which Modality is Better to Treat Acute Renal Failure in the ICU?**

The use of CRRT in the ICU has both anecdotal and scientific rationale. The continuous volume control usually avoids worsening of hypotension in hemodynamically unstable patients. Improved uremia control, more rapid improvement of metabolic acidosis, and control of serum phosphate have all been suggested. Disadvantages of CRRT include the need for anticoagulation, its labor intensive nature, the clotting of the coil in low flow states despite anticoagulation and the clotting that occurs when anticoagulation is contraindicated.

Multiple studies comparing intermittent versus continuous hemodialysis in patients who have acute kidney injury have been inconclusive as to the outcome benefit. Biesin and colleagues suggested that the two technologies have positively influenced each other as CRRT has gone from a low efficiency to a high efficiency treatment while
intermittent dialysis can be done daily and for extended sessions. The influence of the technologies on each other has led to a relatively new modality known as slow low efficient dialysis (SLED), which is traditional dialysis done under low intensity over a longer period of time.63,64 The adaptation of renal replacement technology to the needs of the critically ill has been likened by Ricci and colleagues64 to the plethora of mechanical ventilation options which exist for patients with respiratory failure. Multiple modes of renal replacement therapy in critically ill patients are used interchangeably. If a CRRT coil clots in a patient, clinicians have the option of using SLED or daily intermittent hemodialysis if the critically ill patients can hemodynamically tolerate it.

**Treating Sepsis with Hemofiltration**

The relationship between sepsis and acute kidney injury (AKI) is well known with a large, international observational study attributing 50% of AKI in critically ill patients to sepsis.43 The role, if any, of CRRT as a blood purification treatment in septic patients is not clear. Hemofiltration in sepsis showed beneficial results in animals in 1990 when Stein demonstrated improved hemodynamics associated with hemofiltration in pigs with endotoxemia. These results were confirmed by multiple other animal studies, but they have not been reproduced in humans.55 In a study by Ronco and colleagues,56 a small subset of patients with sepsis had increased survival with high-dose hemofiltration, but the results were not generalizable. Pulsed high-dose hemofiltration in humans has shown lower than expected mortality by acute physiology and chronic health evaluation (APACHE) II score prediction in patients with septic shock and decreased vasopressor requirements.57–59 The use of renal replacement therapy to clear toxic metabolites as a treatment for septic shock requires confirmation with additional research. The literature supporting use of hemofiltration as a therapy consists of small case series, uncontrolled human trials and animal models. A recent prospective clinical trial showed increasing the dose of CRRT in septic patients with AKI did not decrease mortality or improve kidney injury.60 More prospective clinical trials are needed to see if CRRT can be used to decrease mortality as a treatment independent of renal function in critically ill septic patients.

**Summary**

The morbidity and mortality from AKI remains high in critically ill patients despite new dialysis techniques. No significant mortality benefits have been noted using CRRT instead of intermittent hemodialysis, but intensivists now have a wider array of methodologies to dialyze critically ill patients. Limited studies have shown that use of hemofiltration in septic patients may have clinical benefit, but more research needs to be done.

**PULSE OXIMETRY**

**The Early Years**

Historically, the clinical lack of sensitivity to detect hypoxemia is well documented.61 This problem perplexed investigators for over forty years. Pulse oximeters saw limited use in a few pulmonary research laboratories. The oximeters used were bulky, required recalibration after each use and were capable of causing second degree skin-burns. In 1972, the Japanese engineer Ayogi accidentally discovered the basis for modern pulse oximetry while experimenting with dye techniques to measure cardiac output.62 He discovered that by using photoplethysmography, he could isolate the pulsatile variations in oxygenated and deoxygenated hemoglobin. Ayogi noted that the differences in the wavelengths between oxyhemoglobin and reduced
hemoglobin amounted to changes in arterial saturation. His innovation allowed the pulse oximeter to transition from a research device to an important clinical tool.63

Introduction into Clinical Practice

The Minolta Camera Corporation introduced the modern-day pulse oximeter into the United States with little fanfare in the early 1980s. This pulse oximeter was modified by Scott Wilbur for the Biox Corporation who made it less bulky and more convenient for clinical use.64 William New, a Stanford anesthesiologist, recognized the clinical utility of the new less bulky pulse oximeter. He made an adhesive probe and introduced the pulse oximeter into the operating room for noninvasive monitoring of patient’s oxygenation.65,66 William New, Jack Lloyd, and Jim Corenman later started the Nellcor corporation, which became almost synonymous with pulse oximetry.

The pulse oximeter migrated relatively quickly from the operating room to the intensive care unit after New published his work in 1983.67 The spread of the technology was supported by small studies which verified its accuracy in ventilated patients. Mihm and colleagues68,69 affirmed the arterial saturation correlation in 18 critically ill patients and their work was later supported by Van de Louw and colleagues in a larger study in 2001. The oximeter provided real-time insight into ventilator changes when clinicians tried to wean oxygen concentration and the need for arterial blood gases was shown to be reduced.70,71 It was subsequently dubbed the “fifth” vital sign in the critically ill patients.72 By the late 1980s, the pulse oximeter was accepted as a standard instrument for monitoring critically ill patients, but even today no study exists showing its survival benefits.

Limitations of the Technology

Pulse oximetry has significant limitations, which have been well documented in the literature.73,74 Skin pigmentation and dark nail polish have been shown to reduce the accuracy of readings. Anemic patients may have abnormal readings of their arterial saturation. The primary limitation in the critically ill is the inaccuracy of pulse oximetry in shock and those with hypothermia. Pulse oximetry in patients with low cardiac output may not reflect the true oxygen saturation because of peripheral vasoconstriction. Pulse oximeters are notoriously inaccurate when the patient’s saturations are below 70%. A significant plunge in arterial oxygenation is needed for patients to drop their saturation below 100% at high partial pressures of oxygen (this is the flat part of the sigmoid oxygen saturation curve).69

Advancements of Technology

Oximeters have transitioned from reusable probes to disposable ones that can now be applied to multiple sites on patient’s bodies (eg, forehead, fingers, ear lobe). A major advancement in pulse oximetry technology occurred in the mid-1980s with the ability to alter the tones of audible sound as a patient saturation varied. Nellcor modulated their second-generation oximeter pulse tone to different saturations and it was widely adopted (Jeffrey Littman, MD, Camden, NJ, personal communication, May 2008). The major advancement in the 1990s was the Masimo Corporation’s signal extraction technology, which reduced motion and low perfusion artifact.75

Summary

No studies have attributed a specific decrease in mortality to the use of the pulse oximeter in critically ill patients. Its use is omnipresent in ICUs because of physician’s inability to detect subclinical hypoxemia. The pulse oximeter has significant limitations, but technological improvements continue to increase its clinical utility.
MECHANICAL VENTILATION

The Modern Origins

The nineteenth century saw the development of negative pressure ventilation with little clinical utility until Drinker-Shaw invented the iron lung in 1929. This machine was first effectively used to manage the respiratory paralysis caused by polio. The iron lung was a cylindric tank in which patients would be enclosed with only their head protruding. This machine created negative pressure around the patient’s body to create inhalation and exhalation occurred passively. The Cuirass ventilator, an armored sealed vest limited to the thorax that allowed greater nursing access during negative pressure ventilation, was the other primary mode of ventilation for polio patients. The Copehagen polio epidemic of 1952 brought to the forefront the limitations of the iron lung, including its expense, size, the inability to secure a patient’s airway, and pulmonary atelectasis.

Ibsen, an anesthesiologist, understood these limitations when he was brought in as a consultant to help the overwhelmed Danish medical system cope with the epidemic. He suggested the use of positive pressure ventilation (PPV) outside the operating theater. Also, he learned of Bower’s successful use of intermittent positive pressure breathing to supplement negative pressure ventilation for treatment of respiratory acidosis in polio patients. Over a thousand medical students were required to manually ventilate patients during the Copehagen polio epidemic. However, medical centers with less manpower sought machines to ventilate patients. Thus, Ibsen’s advocacy of PPV was the impetus for modern mechanical ventilators and, arguably, for the development of intensive care units. Before his experience, ICUs were set up for the summer polio epidemics and then disbanded.

The Early Ventilators

For PPV, the machine forced air into the patient’s lungs either to a preset pressure or volume. The first volume ventilator to receive widespread praise was Engstrom’s, which he developed in the early 1950s. It was a piston-powered, volume-cycled ventilator, which provided a constant minute ventilation. The ventilator was used successfully in Europe for both postoperative and polio patients. The integration of PPV into United States respiratory practice was drawn by the insistence of cardiothoracic surgeons and anesthesiologists. Morch’s (an anesthesiologist’s) surgical ventilator had been widely used in Europe for fifteen years before it was introduced to the United States in 1955. It represented a definitive improvement in ventilatory management during surgical procedures because it allowed measurement of tidal volume, sterilization of ventilator components in contact with airflow, and it could function in either pressure or volume cycled mode.

An explosion in ventilatory technology occurred over the next sixty years with the early United States pioneers being Bennett, Bird and Emerson. The inventions of all three men were significantly influenced by their World War II experiences with the provision of oxygen for pilots during high-altitude flights. Bennett invented a flow-sensitive valve, which Bower had used to augment NPV with PPV at Los Angeles County Hospital in the late-1940s. Both Bird and Bennett used a variation on this same valve and developed pressure-cycled ventilators that allowed airflow until a predetermined pressure was reached. At this pressure, a valve would close and exhalation would occur. Their ventilators were powered by compressed oxygen. Emerson created a volume cycled ventilator where the tidal volume was delivered by a piston powered motor. In this environment of invention, studies comparing PPV ventilators with iron lungs (which persisted in use till the early 1960’s in the USA) showed the benefits of PPV.
Volume-Controlled Ventilation

As a dramatic increase in the number of patients receiving artificial ventilation occurred in the 1960s, volume ventilation became the ventilatory method of choice. This dominance was because of its ability to deliver a preset tidal volume independently of a patient’s lung mechanics—unlike pressure control ventilation. An alternative method of breath delivery was to provide a fixed pressure through inspiration that was time cycled (pressure controlled). The increased use of PPV was due to the wider development of multidisciplinary ICUs and the ability to obtain blood gases. In Europe, the Servo 900 was the workhorse in the ICUs and it was the first ventilator with capability to display pressure and flow curves and provide the option of either volume or time cycled breaths. (Jennie Haag, Edgewick, NJ, personal communication, August 2008) In the United States, the Puritan-Bennett MA-1 followed distantly by the Ohio-560 were the most commonly used ventilators in the seventies (Fig. 2). Both were bellow-based volume cycled ventilators that were electronically controlled as opposed to the piston-powered ventilators of the previous two decades. They both had high peak pressure capabilities and were able to deliver preset tidal volumes even if patients had decreased lung compliance.

Positive End Expiratory Pressure for Adult Respiratory Distress Syndrome

Patients with decreased lung compliance because of acute infiltrative and edematous lungs occasionally caused physicians great consternation as the patients’ lungs were difficult to oxygenate. Frumin and colleagues were the first to scientifically demonstrate the value of continuous positive pressure inside the expiratory circuit to increase arterial oxygenation. They hypothesized that this positive end expiratory pressure (PEEP) recruited closed alveoli and improved oxygenation. In 1967, Ashbaugh and colleagues recognized in twelve heterogeneous patients a similar difficulty of oxygenation and named it acute respiratory distress syndrome, only to change it in 1971 to adult respiratory distress syndrome (ARDS). Petty saw the value of PEEP in increasing oxygenation and the initial work of his team provided the basis for the treatment of hypoxia (caused by ARDS) with PEEP. PEEP had significant hemodynamic implications.

Fig. 2. Puritan-Bennett MA-1 ventilator. (Courtesy of W. Neal Witwer, RN, CLNC, Galveston, TX. Available at www.nealwitwer.com; used with permission.)
effects on critically ill patients, including decreasing cardiac output and arterial blood pressure, therefore it was recommended that PEEP levels greater than 10 required vigilance by intensivists.95

PEEP was first applied by immersing the expiratory limb of the ventilator in a small bucket of water with the depth of immersion representing the PEEP applied by the ventilator. The introduction of PEEP valves with threshold resistors allowed clinicians to avoid this encumbrance.

*Evolution of Ventilatory Modes*

Besides optimizing methods to oxygenate patients, more thought was given to weaning patients from ventilators. The classic mode of ventilation for volume control was controlled mandatory ventilation (CMV). The ventilator provides every breath and this result is achieved only by heavily sedating the patient. Assist-control ventilation (AC) is a preset tidal volume delivered to patients, but patients can initiate additional breaths. In 1973, Downs and colleagues introduced intermittent mandatory ventilation (IMV), which allowed patients to receive their preset ventilatory support and then initiate their own breaths receiving fresh humidified gas flow from a separate circuit. Between positive pressure ventilator breaths patients were able to inspire and generate their own spontaneous tidal volume without ventilator interference.96 IMV was later refined to synchronized intermittent mandatory ventilation (SIMV) to prevent patients from initiating breath when the ventilator was attempting to provide a breath (“stacking”). While the merits of IMV were vigorously debated in the medical literature, IMV was widely adopted into clinical practice. The MA-1 design was limited by the need for an additional circuit to be setup for IMV. Emerson recognized the importance of the new ventilatory mode and was amongst the first to invent a commercially viable machine that incorporated IMV.87

*Pressure Support Ventilation and Pressure Control Ventilation*

In the early 1980s, Norlander proposed a method of ventilatory support to help patients with their inspiratory effort.97 Pressure was applied in the inspiratory limb to help augment patients’ tidal volume and decrease their work of breathing. This mode of ventilation, pressure support ventilation (PSV), was revolutionary as patients controlled their own respiratory rate and had partial control over their tidal volume.80 It was primarily used to wean patients from the ventilator and, by 1998, it was reported that 45% of practitioners used PSV for weaning.98 PSV was widely recognized as an important modality and it was incorporated into ventilators of that era including the Servo 900c and Bennett 7200.

PCV was available on most ventilators by the mid-1990s. The recognition of the significant impact of volutrauma on the lungs and a greater tolerance of permissive hypercapnia made clinicians reconsider PCV.80 Inverse ratio ventilation (IRV) was a modification on PCV in which the patients’ inspiratory time for ventilation was made longer than their exhalation time. IRV was less frequently applied using volume ventilation with an inspiratory hold. The modality was designed for patients who were difficult to oxygenate (eg, ARDS), but it had significant limitations. Because of the prolonged inspiratory phase, patients had to be heavily sedated or paralyzed, and the benefit in oxygenation was at the cost of high mean airway pressures cardiovascular compromise.99

*Microprocessors-Based Ventilators*

The advent of microprocessors in ventilators allowed for peak inspiratory pressure, mean airway pressure, and continuous positive airway pressure to be measured.
Safety was improved because of internal alarms, which sensed abnormalities when ventilating patients. The mechanics of ventilators became enhanced, for example, the transition from inspiration to expiration in the machine was now electronically controlled because the ventilator sensed the end of inspiration as opposed to previously waiting for pressure to decrease. The first commercially available ventilator in the United States to have a microprocessor was the Bennett 7200. Microprocessors allowed for the development of graphics to enable real-time visualization of pressure flow and volume during ventilatory cycles. A few examples of ventilators that provide advanced graphics are the Servo-I, Drager-Evita-4 and GE Care Station-Engstrom.

**Airway Pressure Release Ventilation (APRV)**

In 1987, Stock and Downs introduced airway pressure release ventilation (APRV) as a new mode of ventilation in anesthetized dogs. They asserted that contemporary mechanical ventilation modes because of their historical design for patients with neuromuscular illness were inadequate for patients with intrinsic lung disease. APRV is the application of continuous positive airway pressure (CPAP) at alternating high and low levels in time limited cycles (T_high and T_low). APRV has a time sensitive pressure release valve in the expiratory circuit which decreases pressure in the airway to aide exhalation. The mode currently allows the physiologic benefits of spontaneous breathing. The mode as currently used employs a very short T_low which is referred to as a “dump” period, which facilitates CO_2 removal. Literature is limited as to any advantage or superiority of APRV over other modes.

**Summary**

The merits of PPV were recognized during the polio epidemic of 1952 and that experience helped spur generalized ICUs. A great number of innovators and investigators have developed ventilators that have contributed to the care of the critically ill and injured patients. Modern day intensivists on a daily basis must decide which mode of ventilation is compatible with the needs of an individual patient. Moreover, newer ventilators allow intensivists to combine dual breaths. In the future, new insights and design innovations in ventilators may advance beyond the current machines and modes of ventilation.

**SUMMARY**

The history of technology in the ICU spans five decades of pioneering work by dedicated investigators from medical, bioengineering and other fields. Technology has played a significant role in the advancement of the practice of critical care medicine. The understanding of hemodynamics, first by the PAC and subsequently by echocardiogram, has enhanced our understanding of the physiology of critical illness. The development of CRRT has allowed practitioners to dialyze ICU patients; the monitoring of oxygen saturation with pulse oximetry has provided continuous feedback for early warning systems. Mechanical ventilation and its history parallel the development of ICUs and its further development will likely lead to better care for patients. Technology will continue to play an important role in the ICU as new challenges in the care of critically ill and injured patients are faced.

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