Applied Respiratory Physiology: Use of Ventilator Waveforms and Mechanics in the Management of Critically Ill Patients

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Graphical waveforms have become ubiquitous in clinical care. Using and understanding pictures and symbols is a daily activity. Humans are neurologically equipped to understand symbolic information and have done so for millennia. Cave drawings are examples of using images to convey information. The same approach used in understanding "art" is needed to use ventilator waveforms effectively. Didactic study, frequent viewing, and understanding of the background of the artist (artistic context) are needed to fully appreciate art. Using waveforms to care for patients requires understanding of the clinical context under which they are obtained, factors that affect their creation, and artifacts that interfere with interpretation. This article summarizes the presentation and discussions at this Journal Conference on ventilator waveforms in relation to lung and chest wall compliance, resistance, carbon dioxide kinetics, hemodynamics, specific modes of ventilation, specific lung diseases, and ventilator-weaning. *Key words: waveforms, mechanical ventilation.* [Respir Care 2005;50(2):287–293. © 2005 Daedalus Enterprises]

Introduction

A diverse group of scientists and clinicians met in Cancún to discuss ventilator waveforms and the physiology that undergirds their creation and interpretation. A wide variety of papers were presented, and these form the content of the January and February 2005 issues of RESPIRATORY CARE. This conference was unique among RESPIRATORY CARE Journal Conferences. Usually the conference topic or theme is narrow and related to a specific therapy, disease, or environment; this conference was broad and far-reaching, considering everything from ventilator graphics to carbon dioxide kinetics to hemodynamics. The commonality was use of these monitoring modalities in the critically ill. Many of the participants had concerns about the breadth of this conference, its logic, and the fact that there is almost no scientific literature specifically related to waveforms, from which to draw. Over the 2 days of the conference, ideas began to gel. As in previous Journal Conferences, the expert audience interaction (reported in the discussions that followed each presentation) focused attention and enhanced the value of each individual presentation, identifying areas of common understanding and pointing out those areas of important knowledge deficits and differences of opinion. Throughout the conference, enthusi-

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asm for waveforms and the conference grew and all agreed that useful information was presented and discussed.

Waveforms and Art

Waveforms remain difficult to understand and discuss, because of the immense amount of information contained within the waveform and the need to understand the context and the clinical conditions in which it is recorded. Waveforms are more complex than simple measurements or numbers. Scientific analysis of clinical decisions using waveforms is not easy, and this problem is a huge impediment to our understanding and accepting these important clinical tools. Familiarity with and comfort in using waveforms requires frequent exposure and experience, but viewing waveforms does not replace the clinical examination; waveforms are supplementary and useful in recognizing, evaluating, and understanding clinical issues. Most of the factors that affect waveforms should be identified in caring for the patient and then confirmed or refuted by examining the available waveforms.

Waveforms are similar to works of art. They convey large amounts of information in a compact and compressed form. Waveforms and traditional art contain information not easily described with words or numbers. "A picture is worth a thousand words" is an often-quoted saying that indicates the value of visual art in conveying information. Often a picture evokes a feeling as well as giving specific details about the subject. Sometimes viewing a waveform evokes a similar type of response in the clinician, a *feeling* that something is happening with the patient.

Humans have been using pictures and other art forms since our divergence from other primates hundreds of thousands of years ago. It seems human neural systems are uniquely designed to appreciate symbolic representations of objects, moods, and emotions. Figures 1 and 2 show petroglyphs (waveforms) from a sandstone rock in Nevada. Though these petroglyphs are relatively new (3,000–4,000 years old), there are other petroglyphs and pictographs that are 50,000–100,000 years old. The exact meaning of these waveforms is not known, but some familiar objects are clearly identifiable. The message contained in these pictures could be spiritual, historical, or even safety information; or they could simply be concepts unique to the prehistoric artist and his audience. It is likely that the humans who saw these images thousands of years ago understood their significance and meaning precisely. The only way we would know for sure what they mean would be to understand the conditions under which these art forms (waveforms) were created, who the artist was, and the conditions at the time of their creation. In terms of art, this is called the *context*. The need to know information about the process of creation for interpretation is true of physiologic waveforms as well. Removed from the patient's bedside, the information and actual meaning of a waveform is difficult to ascertain; we need the clinical context to fully appreciate the meaning of the waveform. To apply the information contained in a waveform, we must understand how it was obtained and what was going on with the patient at the time of its creation; in other words, the clinical context.

Fig. 1. Petroglyphs, presumably representing humans, on a cliff near Las Vegas, Nevada.

Like art appreciation, understanding waveforms takes practice. Like art, information about waveforms cannot easily be conveyed in words or taught in didactic lectures. For these reasons, the proceedings of this Journal Conference are liberally laced with pictures of waveforms. Each author tried to encapsulate the information about his subject matter in words, richly illustrated with pictures. Some of the topics and presentations overlap. Some of the papers use the same waveform illustrations, and the authors apply slightly different interpretations to the data and waveform. This is to be expected. As with art, the viewer's interpretation is influenced by his or her experience. The reader should not be discouraged if his own interpretation differs from that of the author.

As a participant in this conference, I observed that almost all of the presentations included something that was "old" as well as the latest information. This is not necessarily a deficiency, because what is "new" is almost always "old." Many new ideas have been around for a long time; some have only recently been supported by new data and have now been accepted as truth. For instance, the idea that airway pressures (positive end-expiratory pressure and ventilation pressure) during mechanical ventila-

Fig. 2. Petroglyphs on a rock face near Las Vegas, Nevada.

tion of patients with acute respiratory distress syndrome (ARDS) should result in optimal lung compliance during tidal ventilation is an idea that has been published and discussed for at least 25 years, but recent data have strengthened its support, and waveform analysis has provided new ways to identify this optimal balance. Whether to use inflection points determined during an inflation curve or a deflation curve to determine the balance between continued recruitment and over-distention is a question not yet answered, but was considered in several of the papers in this conference.

Papers and Topics

The conference and presentations were divided into 3 general areas: physics and physiology; ventilator graphics and modes of ventilation; and using the waveform to manage the patient on a ventilator. I will present a brief summary of the main ideas from each paper. When appropriate I will mention at least one "old" idea that was discussed and share a memorable word, phrase or concept that was used during the oral presentation. By its nature, this approach is a very personal one. It will ignore most of the valuable content of each presentation, but I hope to give you a flavor of the actual conference and whet your appetite for reading the entire paper.

Warren Sanborn began the conference by reviewing with us the generation of the signals we see on our ventilator display screens.[1] He told us that all we really needed to know was: signals come out of the patient, go into the ventilator, and pop up on the screen. He said he could have stopped his talk right there except for a few little details. One of these is the transfer function; this isn't where you give a piece of paper to the bus driver; instead, it is probably the greatest problem that engineers and clinicians have with mechanical devices. Generally speaking, the system variable of clinical interest is not smooth, and it contains a lot of extraneous information or "noise." In a perfect engineering world, the transfer function provides proportional output for each unit of input. The clinician may like straight or smooth lines—their artistic simplicity is awesome—but straight lines are rarely seen in engineering. With filtering and smoothing, the transfer function attempts to capture important information and display it in an easily recognizable way. Warren told us that with step-changes in variables, rather than gradual changes, engineers go crazy because it's very difficult (impossible?) to simulate those changes with mathematical formulae. But that problem led to the best quote that I heard during Warren's talk: "ferocious transients." This is probably as significant to an engineer as "lethal arrhythmia," "failure to ventilate," or "malpractice action" is to a clinician. I know "ferocious transient" generated a strong emotion in me.

Other thoughts that Warren shared included the notion that what we think of as "measurements" are really only estimates. This is very important to remember in evaluating equipment limitations; the analogy of trying to measure a sewer pipe and a hair with the same micrometer explains the problem with using the same flow meter with pediatric and adult patients.

Lluís Blanch evaluated the mechanical signals derived from ventilator circuits and the physiology underlying the generation of these signals.[2] He described resistance and compliance calculations and how these are affected by transpleural pressure variations. He noted that differences in interpretation depend on whether the variables are calculated during inspiration or expiration, or obtained with intermittent occlusion techniques. He differentiated and discussed 2 components of airway resistance: the initial pressure drop due to the elastic properties of the lung and chest wall, and the later pressure drop caused by the internal redistribution of volume influenced by the time-constant inequalities of the lung. Lluís described the "old" idea of using the upper and lower inflection points to manage ventilation in ARDS, but shared the "new" idea that we really are no longer sure what the inflection points actually mean. He articulated the concern about alveolar recruitment and derecruitment during tidal ventilation and how it affects lung function. His best comment about what to do clinically with the pressure-volume curve was, "It is not exactly clear and probably isn't as simple as we thought." (I never thought it was simple!) Lluís introduced the concept of stress index to evaluate and quantitate the effect of mechanical ventilation on the lung. Using the shape of the dynamic pressure-time profile during constant-flow ventilation by Ranieri et al,[3] Lluís, gave us the memorable quote, "The ventilator settings are good when the curve is a straight line and does not point to the ceiling or the floor." Though he says he's a scientist, he's really an art critic giving his opinion of what constitutes good and bad art (ie, waveforms).

The next paper, on esophageal and gastric pressure measurement, was presented by Josh Benditt.[4] Josh is the only "real" artist in the group, being an accomplished sculptor. As far as I know, he is the only presenter who owns a kiln. One of the things Josh is particularly interested in is the effects of abdominal pressure on lung evaluation and function. An advocate for measurement of esophageal pressure, Josh suggested that esophageal pressure measurement is easy to perform and has demonstrated that to his students by making the measurement on himself. He noted that observations of cardiac oscillations from the esophageal balloon make correct placement of the device easy; thus, recognizing a waveform pattern is useful in reference to the clinical context. Esophageal pressure measurement is useful for confirming the diagnosis of diaphragm paralysis and assessing missed triggering during mechanical ventilation. He suggested that bladder pressure may be a reasonable substitute for the esophageal balloon, which is now almost an historical relic and probably only available on eBay! His most memorable quote was, "The esophageal balloon might have been the Swan-Ganz catheter of the pulmonologist." Of course, the Swan-Ganz catheter is over 30 years old and its use remains under attack! Josh also used the term "mélange of technology" to describe the variety of devices in use clinically. I find that phrase memorable, poetic, and artistic (but I don't actually know what it means).

Scott Harris discussed in great detail the lung and thorax pressure-volume curve.[5] He stressed the importance of the pressure-volume relationship and illustrated multiple techniques for measuring it. He described the physiologic principles underlying the curve and the variations caused by the techniques used to generate it. He was particularly informative about the effects of the chest-wall compliance properties on alterations of the pressure-volume curve. This led to a discussion of the problems and concerns with obesity; how these affect the pressure-volume relationship, and how one can go about separating them from lung issues. In reality, the abdomen is part of the chest wall. Scott talked about static versus dynamic compliance measurements. He described the concept of a dynamic decline in pressure, and while some have advocated this measurement, Scott described 3 methods to take this into account. The most notable was the dynostatic method. After a detailed analysis of the problems and alternatives to examining a pressure-volume waveform for making adjustments in patients with ARDS, Scott stated, "The pressure-volume curve is critically ill, but not dead."

We learned quite a bit about the information contained in exhaled carbon dioxide curves from John Thompson.[6] He told us the 4 things he teaches to his students. First, P_{aCO_2} is at least equal to end-tidal carbon dioxide (P_{ETCO_2}). Second, a large difference between P_{aCO_2} and P_{ETCO_2} suggests high ventilation/perfusion ratios. This is most likely due to excessive ventilation or chronic obstructive pulmonary disease (COPD). Third, there is a difference between the P_{ETCO_2} during tidal ventilation and that during a forced vital capacity maneuver. The P_{ETCO_2} approaches P_{aCO_2} during a prolonged exhalation. Rapid breathing lowers P_{ETCO_2}. Fourth, an acute fall in P_{ETCO_2} is most likely due to a fall in cardiac output, which is caused by under-perfusion of the lung and an acute rise in dead-space ventilation.

John showed the capnograms that he uses to teach recognition of common clinical conditions, including bronchial rather than tracheal intubation, and effects of a pneumothorax. John contrasted the carbon-dioxide-versus-volume and carbon-dioxide-versus-time curves, which are more commonly available clinically but that may give us less useful information. John mentioned using the Fick equation to calculate cardiac output, but suggested there was only one "direct way" to measure cardiac output. Although it's not a perfect technique, the Guillotine, which was developed by a physician in the 17th century, can be used in all patient populations and is a technique that is 100% accurate for measuring cardiac output. This is much better than current measurements techniques, but, unfortunately, it carries an unacceptably high mortality risk (100% when properly used) and can be used only once with each subject. And it may produce unusually high results because of catecholamine release in the subject!

Lluís Blanch also presented a paper on dynamic hyperinflation (intrinsic positive end-expiratory pressure [PEEP]).[7] Waveform analysis makes dynamic hyperinflation easy to identify and manage. He showed us that dynamic hyperinflation arises with a long inspiratory time or a short expiratory time, and is easily identified on the waveform by the fact that the baseline flow does not return to zero at end-expiration. Lluís reminded us that the problems with intrinsic PEEP (besides measuring it) are its effects on ventilator triggering and hemodynamics. Using waveforms to identify and manage intrinsic PEEP allows reduction in both inspiratory and expiratory work of breathing. The adverse effects on hemodynamics can be recognized as well.

We switched gears and considered specific ventilation modes and their graphic representations. In a presentation that does not correspond to an article in these special issues, Bob Campbell talked about volume-control and pressure-control ventilation. He stated that ventilator graphics are essential aids to optimize ventilation settings, to monitor ventilator performance, and to manage patient mechanics. They provide important information to identify the responses to changes in settings and changes in diseases. The ultimate goals in monitoring waveforms are to avoid complications and improve patient outcome. Bob reminded us that this goal includes a large list of possibilities and "good if you can do it", but he told us that we should be "using graphics to look for spontaneous efforts in flow waveforms" because "that's where the money is." What came over clearly in this discussion was that although you must understand the context in which the waveform is obtained, there are times when waveform clues precede clinical signs and clinical problems. Bob advises to not ignore the graphics.

Dean Hess discussed waveforms and pressure support ventilation.[8] This spontaneous-breathing-support mode depends on clear identification of a trigger signal from patient inspiratory effort. This creates issues with flow, pressure, and inspiratory cycling off. Each particular manufacturer of a pressure support ventilation device chooses to emphasize one or the other signal off-cycling method, and each device has its own problems. Dean emphasized the many problems with pressure support ventilation can be detected with waveform analysis. One can identify problems with early or late initiation or termination of a breath. The pressure support could begin too late, in which case there will be a mismatch of flow and demand, or the support may cycle off too late, which increases expiratory work of breathing. Circuit issues can also interfere with appropriate triggering and cycling and cause problems. Dean also advocates looking at the graphics, but he gets credit for emphasizing and articulating the "eyeball test," which means *looking at the patient* and not relying solely on the waveforms. Dean started his presentation by stating that "Pressure support ventilation is a simple mode," but, after reading Dean's paper, I'm not so sure anyone will believe that statement. The highlight of Dean's presentation was when, during the discussion, Neil MacIntyre stated, "We don't even use pressure support anymore." Is nothing sacred?

Rich Branson presented a paper on using waveforms with dual-control ventilation modes.[9] A prior commitment to a family event kept Rich from attending the conference, but he did, however, personally present his paper. Using the most sophisticated "cave picture writing technique," Rich was at the conference on a DVD, and his message included issues of concern with dual-control modes. One concern is that lung (and circuit) compliance changes and patient effort changes may be treated the same by the ventilator. In addition, there is no trend data evaluation being recorded, so it is difficult to track the path the ventilator took to determine its current settings. Also, there is no patient-outcome data suggesting actual benefit. Most importantly, the automatic ventilator responses to changes may, at times, be deleterious to the patient. The same signals that are used in generating waveform graphics are used to make automatic changes; they are subject to the same artifacts and distortions; and Dean's "eyeball test" is missing. The approach to dual-control ventilation modes should be cautious. Though Rich was not at the conference to answer questions, his best videotaped comment struck a chord with the audience: "If I had come to Cancún [to participate in the conference] instead of being with my family, I would be living in the basement for a long while!"

Jon Nilsestuen talked about establishing ventilator-patient synchrony, and, of course, that's a most important problem that has led to the development of "new" and refinement of "old" ventilation modes.[10] Jon described this as a problem of making 2 pumps work together: the patient's ventilatory system and the ventilator. That systems approach seemed novel to me; I had never really thought of the issue that way, but it seems to be a perfect analogy and helps the "artist" in me better understand and gives me a picture of the problem.

Jon identified that the problems with synchrony are: triggering, rise time, and breath termination. Jon showed waveforms that illustrated those problems and asked us to identify the specific problems. He uses these cases in his many lectures about waveform interpretation. He shared his frustration that "even experienced clinicians often fail this (simple?) test." As I have asserted before, I believe waveforms are "art," and art appreciation and understanding requires education and experience; you don't just read a book on art and then understand art. Understanding requires practice and experience. The good news for Jon is, he has long-term job security: there is a continuing need for waveform-education. Hopefully, this Journal Conference will serve a stimulus for some people to begin—and others to continue—learning to interpret ventilator waveforms. Jon and I share an interest in bicycling and his most memorable quote was to suggest that intrinsic PEEP be called, "cycle-PEEP" instead of "auto-PEEP," referring to the problem of ventilator-cycling/breath-termination.

Luca Bigatello presented a paper on waveforms and ARDS.[11] While reviewing the "old," he added several new twists: he discussed the role of treatments and causes of increased airway resistance in ARDS, the effects of abdominal pressure on ventilation parameters, the inhomogeneous distribution of pressures in the chest, and the effects of prone position. He reiterated that there has been no clear improvement in patient outcomes from any of those interesting ideas, but his best statement was that he strongly "believes that a better understanding of the physiology of disease and therapy will be developed and will improve patient outcome." Luca must be an artist at heart, given that optimism, since we've come so far in 30 years in our understanding of physiology, but have done so little in improving outcomes!

Waveforms and COPD was the subject of the presentation by Rajiv Dhand,[12] who contributed the best animated slides of the conference, which illustrated moving graphics waveforms and the effects of COPD. These moving pressure-time and volume-time curves were spectacular. It is a shame they cannot be included in the article that commemorates his presentation. To create figures for this conference, most of us just scanned in printed graphs and waveforms, but Rajiv created his own illustrations, which looked very real. It takes time and a true artist to be able to do that well. He used a word new to me, "dashpot," when presenting an analog model of the respiratory system. I still don't know what it means. In addition to those beautiful illustrations of mechanical ventilation of patients with COPD, Rajiv also discussed the problem of secretions in the airway and how they affect the waveforms.

In my presentation to the conference,[13] I talked about heart and lung interactions. Basically, the physiology can be summarized by understanding the effects of intrathoracic pressure on venous return to the right heart. Other minor effects on the various cardiac chambers (right and left ventricular afterload, left-ventricular preload and geometry, interaction of lung volume and pulmonary vascular resistance) complete this complex analysis. These complicated relationships can be investigated clinically by asking the question, "does the patient need more fluid?" That is a simplification but a useful one. The answer may be found in waveform analysis—in this case, ventilator-induced changes in intra-arterial-pressure line recordings. The systolic pressure rises and then falls with positive-pressure ventilation, and the degree of variation correlates with responses to fluid administration in many patients. The practical answer is as simple as that. The complex physiology of heart and lung interactions is entertaining to consider but difficult to apply.

The final paper of the conference was presented by Neil MacIntyre. He discussed the uses of waveforms during weaning from mechanical ventilation.[14] We knew the information he was about to present was "new" because he continued to add to his talk (using a computer!) until 5 min before his presentation began. Neil reviewed how mechanical ventilation can unload the respiratory system, the value of spontaneous breathing trials during weaning—though he didn't want to call it weaning anymore; in fact, he suggested that we abolish the word "weaning." He also suggested that we use a comfortable ventilation mode between daily spontaneous breathing trials. Neil described a new device for which he holds the patent: the *loadometer*. This device is attached to the patient and measures the respiratory work load that is being produced and compares it to the maximum the patient is capable of generating. With this *loadometer* the level of support can be titrated and patient work monitored. Of course, the *loadometer* exists only in Dr MacIntyre's mind, but being an artist, Neil showed a picture of how the device would work in optimizing the application and withdrawal of ventilatory support. His best quote was, "All a ventilator can do is support the patient and screw things up," and as trite at that sounds it truly summarizes what we've learned about mechanical ventilation in the last 30 years. The less artificial ventilation, the better.

Summary

This Journal Conference ended much as have previous conferences, with the presenters feeling that something important had occurred. Most of us changed our views on many of our old ideas, as well as acquired some new ones.

Fig. 3. Is the sun rising or setting?

I hope the readers of these papers and their discussions will have the same feeling of accomplishment and enjoy the didactic and interactive aspects of the conference. As with art, the context of the image or waveform is important to understanding. In Figure 3, is the sun rising or setting? Only the context in which the image was obtained will answer that question.

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