One of the most important roles a respiratory therapist has in the critical care area is to tailor mechanical ventilator settings to maximize therapeutic benefit and minimize patient harm. Recent evidence suggests that the ventilator settings used may injure the lungs and possibly influence injury to other organ systems too.1-3

The problem
Ventilator-induced lung injury is thought to be caused by at least two mechanisms. While excessive tidal volume (VT) and/or pressure may overdistend lung units at peak inspiration and cause stress injury, insufficient positive end expiratory pressure (PEEP) may allow lung units to collapse at end-exhalation; and the repetitive opening and collapse during tidal ventilation may cause injury from elevated shear forces. Monitoring the volume-pressure relationship of the respiratory system may help determine the ventilator settings that could minimize these harmful effects.

A possible solution
Graphic representation of the volume-pressure (VP) relationship (that is, the VP curve) has been suggested as such a tool.4-9 The VP curve of patients with acute lung injury generated under static conditions often has a sigmoidal shape, as shown in Figure 1. At the beginning of inspiration, pressure rises while minimal volume enters the lungs. As pressure continues to be applied, lung units open up and a greater degree of volume is delivered per unit of pressure. This is reflected in an upward inflection in the VP curve, which signifies recruitment of collapsed lung units. As the lungs inflate, pressure and volume rise together in a fairly linear manner until the stretch limit of the lungs is reached.
Pressure rises more quickly as further volume enters the lungs, possibly suggesting overdistension of lung units. The intersection of tangents drawn to the lower flat portion (line A, Figure 1) and to the linear mid-portion (line B, Figure 1) of the curve help identify the lower inflection point (LIP), also known as the Pflex. It has been recommended that PEEP be set slightly higher than the LIP. The intersection of tangents drawn to the upper flat portion (line C, Figure 1) and to the linear mid-portion help identify the upper inflection point (UIP). It has been recommended that VT and/or peak distending pressure be limited to pressures below the UIP.

The inflation limb of the VP curve can be graphically expressed using either static or dynamic methods. Static methods obtain pressure measurements following several seconds of zero flow while dynamic methods take the pressure measurements during constant inspiratory flow. The LIP can usually be determined before a volume of 1.0 L is reached, but volumes of 1.5 to 2.0 L may be needed to assess the presence of a UIP. Pressure is usually limited to 40–50 cm H₂O. The deflation limb is best generated using a static method because expiratory flow must be controlled.

The classic method of constructing a static VP curve uses a calibration syringe to inflate and deflate the lungs with 50 to 100 mL incremental volumes while measuring the pressure after several seconds of zero flow at each volume increment. Before any volume is injected, the lungs are allowed to fully deflate so trapped gas (intrinsic-PEEP) does not influence the mechanics measured. Both the inflation and deflation limb of the curve can be measured in this manner.

The area within the inflation and deflation limbs is referred to as hysteresis and is thought to be due to surfactant dysfunction and indicates the presence of collapsed but recruitable lung units. The hysteresis area can be artificially increased when the VP curve is generated using the syringe technique because the volume injected into the lungs rarely comes back out due to continued oxygen consumption by the patient during the procedure. This is one of the reasons why only the inflation limb is often generated. When the deflation limb is to be assessed, it may be best to perform a separate maneuver by inflating the lungs with a large volume and withdrawing 100 mL increments. Another limitation of the syringe method is that the patient must be apneic during the procedure (45 to 90 seconds per limb), which usually requires paralyzing the patient with a paralytic agent. In spite of these limitations, the syringe technique is usually well tolerated without ill effect.

To overcome some of the limitations of the syringe method, other techniques of generating VP curves have been reported in the literature. Several techniques involve leaving the patient on the ventilator and manipulating the ventilator settings. Levy’s inspiratory occlusion method, a static method that has been used by many researchers, incorporates a series of constant inspiratory flow “study breaths.” Static pressures are recorded during a three-second pause at end-expiration (to account for intrinsic-PEEP) and at end-inspiration, while Vₚ is changed in a random order. The patient is ventilated with a normal Vₚ between the test breaths. Some of these researchers use specialized software and modifications to existing ventilators to program the ventilator conditions necessary to conduct the test breaths, while others make the changes manually.

Dynamic VP curves can be generated using a very slow (less than or equal to 15 L/min. for adult patients) constant inspiratory flow, as Vₚ, pressure, and rate are adjusted to obtain the desired maneuver. The best results are obtained using flows as low as 3 L/min., which is challenging to generate with many adult ventilators. An alternative might be to take patients off the ventilator and attach them to a calibrated flow meter running at a constant flow while measuring the pressure and volume dynamically with standard pressure and flow monitoring systems or a special respiratory mechanics system.

Most new-generation ventilators have the ability to display a variety of graphic patterns, there is increasing interest in VP curves within the respiratory care research community.
including the volume-pressure loop. A tempting, but very misleading, tendency might be to try to determine the LIP and UIP using ventilator settings similar to those used during a normal ventilator breath. If these inflection points are obtained with inspiratory flows normally used to ventilate patients, the results will be greatly exaggerated (see Figure 2). The resistive energy from the relatively high inspiratory flow causes the inspiratory limb of the VP curve to shift to the right and will result in elevated LIP and UIP values. If a decelerating fixed flow is used, the UIP will not be as greatly influenced because of the relatively slow flow at end-inspiration, although the LIP will still be unreliably high.

**Potential significance of the UIP and LIP**

Although the literature supports using the LIP and UIP to help determine the best level of PEEP and plateau pressure to apply, recent studies indicate that this strategy may not be so straightforward. For example, the UIP may not always indicate overdistension. When the slope of the linear mid-portion of the VP curve changes more gradually and is less abrupt, this change may represent the end of alveolar recruitment and not overdistension.

When the change in slope is more dramatic, it most likely indicates overdistension of lung units. However, if the transpulmonary (alveolar minus pleural) or distending pressure is much lower than if these elements were normal. During this scenario, lung overdistension may not be present even when high airway pressures are encountered because pleural pressure is elevated.

In spite of these limitations, it is still probably prudent to observe dynamic VP curves during normal tidal ventilation for overdistension; and if a UIP is grossly present, consider reducing VT and/or applied pressure. The presence of the LIP, as well as the oxygenation response to PEEP, appears to be influenced by whether acute lung injury is the result of a direct pulmonary injury (such as pneumonia) or an indirect non-pulmonary insult (such as sepsis or polytrauma). Partitioning the respiratory mechanics of the total respiratory system into its chest wall and lung components with the aid of an esophageal balloon may be important in providing a more complete assessment of the issues involved.

The LIP is thought to indicate the pressure at which a significant amount of alveolar recruitment begins. It has been shown that recruitment continues to take place throughout inspiration and is dependent on the VT, as well as the level of PEEP chosen. Rather than focusing entirely on the inspiratory phase, attention should be placed on expiration, too. PEEP helps maintain patency of lung units that are recruited during the previous breath. Rather than setting PEEP to the pressure level required to initiate recruitment at zero end-expiratory pressure, PEEP should be set to a level slightly above the pressure required to keep recruited lung units open at end-exhalation (that is, above the critical closing pressure). The closing pressure might be determined using the deflation limb of a static VP curve. For reasons already discussed, however, the deflation limb is relatively hard to determine; and an easier and more practical method is desirable. One method might be to monitor oxygenation as continuous positive airway pressure (CPAP) is reduced following a recruitment maneuver (see below).

It has also been shown in animals that a lower level of PEEP may be required to keep lungs open following full lung recruitment, such as that obtained with a recruitment maneuver using a CPAP of 30 to 40 cm H₂O for 30 to 60 seconds, compared to PEEP set to LIP.

These studies suggest that PEEP set to LIP may not be the ideal level because it is associated with higher peak and plateau pressures than those encountered using a lower PEEP in conjunction with a recruitment maneuver.

Another important point to remember is that the information provided by a specific VP curve is relevant to the state of the respiratory system only at the time the curve was per-
formed. A progressive time-dependent recruitment may affect the slope of the curve (compliance) after PEEP is applied, as well as the lower and upper inflection points.

If the number of abstracts related to VP curves that were presented at the AARC OPEN FORUM this past December is any indication, there is increasing interest in this topic within the respiratory care research community. Seven abstracts were published in the November 1999 issue of Respiratory Care, compared to only three (continued on page 108).
Mechanical Ventilation
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last year and one the previous year. Although the syringe technique can be performed safely, it can be fairly labor intensive; and meticulous attention to detail must be observed to obtain reproducible results.

Automated systems, which allow for a quicker, more reliable, and less complicated procedure for generating VP curves, are needed to help accelerate the clinical research necessary before this technique can become standard bedside practice.

Six Minute Walk
(continued from page 70)

the very conclusion of the walk, and a recovery saturation reading. A notation should indicate whether the test was on room air or with supplemental oxygen and the amount of oxygen used. Reasons for the termination of the test should be clearly documented and may include elevated heart rate, pain, desaturation, or patient request to stop.

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See the “Tools of the Trade” column on the “Table of Contents” in this issue for additional resources on this topic.
Documented oxygen desaturation treated with the application of oxygen and any subsequent arterial blood gases should be documented. Information gathered from the second walk test should be the same as in the first and also be included in the report.

Tests that are not performed secondary to low saturations should document physician notification of such and any action taken.

Utility of results

Used appropriately, the six-minute walk test can supply critical information for the patient and the clinician. It can serve as an assessment for oxygen requirements, efficacy of the rehabilitative process, and as a part of the selection criteria for surgery. The test is simple to perform and the results easily appreciated by patients, providing them with positive feedback after an exercise program.

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That simple act of claiming the Vienna sausages unleashed something in me I didn’t know I had. Call it survival instinct. Call it the hunter-gatherer impulse. Call it compulsive shopping. I grabbed firewood, matches, creamed corn. My mind was quick and urgent. I knew what to buy: everything. But I needed candles, and the Frontier Mart had long since sold out. I headed to K-Mart looking for those half-price Christmas candles that were shaped like stars. They were gone. But I saw a man and his little boy buying two old-fashioned oil lamps and bottles of oil. The boy said, “Dad, we need one more lamp for the bathroom and we’re done.”

My mind clicked. At home I had two antique oil lamps. I grabbed the last bottle of lamp oil, which happened to be bright red. When I paid for it, the clerk looked at me as if I were a wild-eyed doomsday survivalist wacko. I didn’t care. I was a woman on a mission. A woman with lamps to burn. But I needed wicks. I was obsessed with wicks. I shopped at six hardware stores before I had exactly the wicks I needed. I liked the challenge. Preparing for disaster was fun.

All my hunting and gathering done, I headed home. In my kitchen I threaded the wicks into the lamps, lit them, adjusted for minimum smoke, and inserted the chimneys. My lamps burned beautifully. I installed new batteries in my flashlights and arranged them in a neat row on top of the refrigerator. I vacuumed the carpets. Heaven forbid the end of the world might catch me with dirty carpets. I took a shower, my last shower of the millennium, and washed twice. Who knows how long it would have to last.

Next, I laid out my Millennium meal. I spread the red damask cloth on my dining table. I got out my new red chargers to coordinate with the red lamp oil. In the center of each white china plate, I placed a five-ounce can of Libby’s Vienna Sausages. The self-serve pop tops were perfect. I would also serve room-temperature creamed corn. Champagne was chilling on the back porch. I felt enormously satisfied that I had met the challenge, provided for my family. I could hardly wait for the lights to go out.

When John came home, I described the meal to him. He wore the same smirk I had seen on the faces of store clerks all afternoon.

“Go on,” I said. “Laugh. When your stomach growls on New Year’s Day, you’ll be glad for Vienna Sausages and creamed corn.”

He shot me a look that said he preferred a growling stomach.

“If there’s a power outage,” he said, “I’m going to the store to eat ice cream before it melts.”

I turned and headed to my office. “I’ve got to finish writing my column,” I said, “and e-mail it before the power failure.”

“And if there’s no power failure?” John asked.

“I’m throwing the circuit breaker,” I said. “We’ll just pretend.”

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