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CHAPTER 4

Mechanical Ventilator Simulator for Patient-Triggered Cycles and Breath-by-Breath Identification

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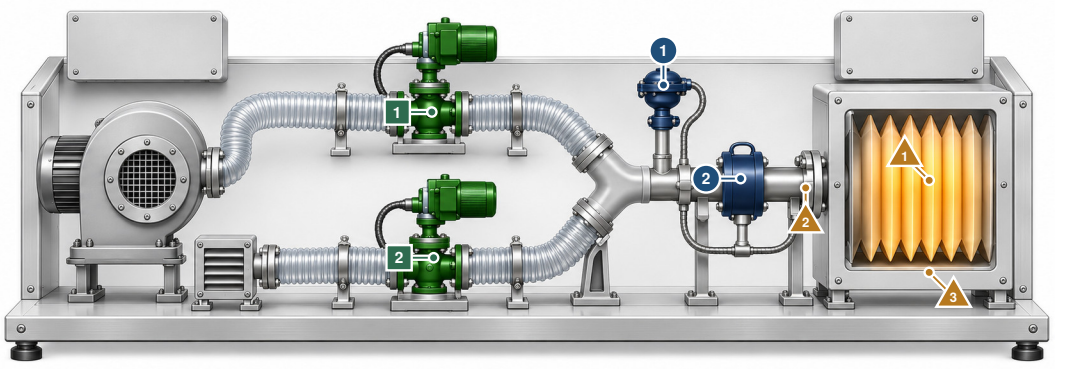
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CHAPTER 4

Mechanical Ventilator Simulator for Patient-Triggered Cycles and Breath-by-Breath Identification



The controller moves 1 inspiratory valve, lets gas in from the blower
2 expiratory valve, lets gas out and holds the end pressure

The controller reads 1 airway pressure at the wye 2 flow at the wye

What disturbs it 1 a lung that stiffens over the hour 2 a leak beyond the flow sensor, at the mask or cuff
3 the patient's own breathing effort

Both sensors sit between the valves and the lung, so a leak beyond them, a stiffer lung or the patient's own pull reaches the controller only through what they read. Illustration, not to scale.

IN PLAIN TERMS **A Breathing Machine That Sees Only the Tube**

The main idea. A ventilator pushes air into the lungs of a patient who cannot breathe well enough alone. It measures only the pressure and the flow where its tubes join the patient's tube. It shapes each breath from those two readings.

The challenge. A leak at the mask looks to the machine like air going into the lungs, and the patient's own breathing pulls on the same tube. The lungs can also stiffen within an hour, so a breath that was safe can grow too forceful or too small.

Why it matters. Too forceful a breath injures the lung, and too small a breath lets carbon dioxide build up in the blood.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	The first page, the fact box of Section 4.1, the first history box in Section 4.2, the try-it boxes, the second history box and the second fact box of Section 4.6, and the key points
Study	50 min	The whole chapter with its pause points and the twelve exercises
Practice	20 min	The first page, Section 4.6, Section 4.7, Section 4.8 and the open challenges

The control question A ventilator measures pressure and flow at the wye, while the leak, the patient's effort and the lung stay hidden. What does each mode hold, and when do the breath the machine reports and the breath the lung receives part company?

Learning objectives

- Compute the plateau of volume control and the volume of pressure control, and name the variable each mode lets go.
- Predict auto-PEEP from the expiratory time in time constants, and name the settings that change it.
- Explain what a leak past the flow sensor does to triggering, cycling and the measured volume, and find the largest leak the valve can hold PEEP against.
- Judge when a per-breath fit of resistance and compliance can be trusted, and what an effort does to it.
- Choose a mode, leak compensation and adaptive support that meet an hour-long target scored on the hidden truth.

Prerequisites Sections 1.4.2 (one compartment), 1.4.4 (identifying the individual), 1.4.6 (actuators that push one way), 1.6.2 (velocity-form PID) and 1.6.4 (scenarios and the challenge).

The app https://apmonitor.com/apps/mechanical-ventilator/

See also Volume 8, Chapter 7 for a cycle that hands one valve between two loops, and Volume 8, Chapter 15 for a hybrid cycle held one impact at a time. Volume 1, Chapter 12 for least squares on inputs that move together, and Volume 1, Chapter 11 for fitted coefficients that absorb what the model leaves out.

4.1 Introduction

Mechanical ventilation is the life support around which modern intensive care units grew [1], and the way a ventilator is set changes survival. A trial stopped after 861 patients with acute lung injury or the acute respiratory distress syndrome (ARDS) gave one arm breaths of 6 mL/kg of predicted body weight with the plateau pressure held at or below 30 cmH_2O, the other 12 mL/kg with a plateau of up to 50 cmH_2O, and mortality was 31.0 % in the first arm against 39.8 % in the second [2]. Pooled data from 3562 patients in nine trials later found the driving pressure, the tidal volume divided by the compliance of the respiratory system, more closely tied to survival than the volume or the PEEP alone [3]. Both findings concern the breath the lung receives, while a ventilator controls the breath its sensors report.

> ✦ **DID YOU KNOW? Ventilators at Home**
>
> By about the year 2000, mechanical ventilation at home was in wide clinical use for chronic respiratory failure, at a prevalence of 6.6 per 100 000 people, with marked variation between countries [4].

The ventilator's view of that breath is narrow. It measures pressure and flow at the wye, where its two limbs join the patient's tube, so a leak past the sensor counts as flow into the lung, the patient's own inspiratory effort is a pressure nobody measures, and the resistance and compliance of the lung are unknown and, in the simulator's cases, halve or double within an hour. A common reading of the screen takes its tidal volume for the lung's, and this simulator shows where that reading fails. In its hour-long challenge, run as shipped in volume control, the monitor reads 418 mL at minute 45 while the lung receives 147 mL, the identified compliance reads 70.6 against a true 31.25 mL/cmH_2O, and the end-tidal CO_2 has risen from 35.5 to 79.3 mmHg, because a 14 L/min leak opened at minute 30 trips the flow trigger 0.44 to 0.48 s into every expiration between minutes 31 and 39. Two neighboring beliefs fail as plainly. Volume control keeps 420 mL going into a lung stiffened to 18 mL/cmH_2O only by letting the plateau climb to between 31.3 and 31.5 cmH_2O, past its 30 cmH_2O limit. Per-breath mechanics are estimates rather than measurements, and a 5 cmH_2O effort pulls the fitted resistance of every breath the patient triggers 21.6 to 21.8 % low and the compliance 10.8 to 12.0 % high on a lung that, relaxed, was identified within 0.5 and 0.2 %.

The class of problem is a hybrid one. Inside each phase of a breath the gas flows continuously, and at each phase boundary a discrete decision is taken, some on a clock and some when a measured flow or pressure crosses a threshold, which is the mixture of flows and jumps that the theory of hybrid dynamical systems treats in general [5]. The taxonomy of ventilator modes uses the same terms, defining a breath by the events that start and stop inspiration, by whether the patient or the machine initiates them, and by the control variable that the equation of motion leaves free [6]. An injection-molding machine that hands its screw from a velocity servo to a pressure servo at a transfer position (Volume 8, Chapter 7), a walking robot whose swing ends at ground contact, and an artificial pancreas dosing around meals (Chapter 2) share that shape, with a cycle whose events the plant partly decides, an estimate refitted every cycle and a limit that counts on every cycle rather than on average. A transfer function between valve opening and airway pressure carries none of it.

The engineering literature reports ventilator controllers on physical lung models, in simulation and in small feasibility studies [7, 8], and the clinical literature finds asynchrony by inspecting recorded pressure and flow [9]. Neither shows the hidden effort, alveolar pressure and leak beside what the machine measured on the same breath. This chapter tells apart, on a simulated ventilator whose patient is hidden from its controller, the breath the lung actually receives and the breath the machine reports, mode by mode, threshold by threshold and estimate by estimate. The modes, the fit, the leak estimate, the adaptive support and the caps all follow the clinical and engineering literature. The chapter gives every equation, constant and rule of the simulator, whose controller reads only two noisy sensors at the wye while an audit classifies every patient effort against the truth. Its nine cases and an hour-long challenge each isolate one way in which the measured and delivered breaths part. All of the application's limits, alarm thresholds and patient values are teaching values. Real ones come from trials such as the ARDS Network's, from the particular standard for critical care ventilators [10], from the asynchrony literature and from the clinician at the bedside, and neither the simulator nor this text offers clinical guidance.

Section 4.2 reviews how ventilation came to be controlled and which variable each generation chose to hold. Section 4.3 gives the lung, the effort, the circuit with its valves and the carbon dioxide store, with the assumptions behind them. Section 4.4 derives four closed forms, for the plateau and volume of a mode, the trapped pressure of an expiration cut short, the edge of the actuator against a leak and the bias that an effort puts into the fit, and checks each against the engine. Section 4.5 describes the breath sequencer, the three valve servos, the per-breath least-squares fit, the volume loop with its protective caps and the alarms. Section 4.6 runs the nine cases and the challenge, Section 4.7 describes the real sensors, valves and controllers, and Sections 4.8 and 4.9 state the limitations and the conclusions.

4.2 Breathing Machines and the Patient Behind Them

Machines breathed through the chest wall before they breathed through the airway. Negative-pressure ventilators appeared in the early 1800s, positive-pressure devices around 1900, and the intensive care ventilator of today began to be developed in the 1940s and has passed through four distinct generations since [11]. The tank respirator of 1929 and the turn to positive pressure in the poliomyelitis epidemics are told in the first history box of this section, and the synchrony problem its authors reported [12] in the second, at the case of Section 4.6 where a patient breathes.

The positive-pressure modes that followed differ in which variable they hold, and the taxonomy now used to classify them starts from the equation of motion, defines mandatory and spontaneous breaths by whether the ventilator or the patient starts and stops them, and combines control variables and breath sequences with targeting schemes [6]. Pressure support, a pressure assist that augments each spontaneous effort with a clinician-selected airway pressure, was studied in 1986 on 15 stable patients and on a mechanical model of them, and was found to improve comfort and reduce the patient's work [13]. Proportional assist went further in 1992 by applying pressure according to the equation of motion so that the ventilator amplifies the patient's instantaneous effort while the

patient keeps control of the volume and both durations [14]. Closed loops on the ventilator's own settings followed. An adaptive lung ventilation controller of 1994 adjusted the rate and the inspiratory pressure toward a target alveolar ventilation from measured lung mechanics and dead space, and on a physical lung model with restrictive, normal and obstructive settings it answered steps in 48 to 81 s with 5.5 to 7.9 % overshoot [7], and a review of 2011 expected closed-loop control on most aspects of ventilatory support [11]. The particular standard for critical care ventilators, current in the United Kingdom as BS EN ISO 80601-2-12:2023, covers their basic safety and essential performance, and it counts a ventilator as a physiologic closed-loop system only when a physiological patient variable adjusts the therapy settings [10].

> ⧖ HISTORY **From the Tank to Positive Pressure (1929 to 1952)**
>
> By 1928 rescue squads in the United States and Canada had discarded the resuscitators that forced air in and out through a valved face mask. The tank respirator described in 1929 sealed the body below the neck in a sheet-metal cylinder, while the head stayed at room pressure. Two blowers and a rotating valve, driven by a variable-speed motor, lowered and raised the pressure around the body, up to about 60 cmH_2O at 10 to 40 breaths a minute. A child paralyzed by poliomyelitis was kept in it almost continuously for 122 hours [12]. In the polio epidemics tanks were built in large numbers. From 1949 a valve that added positive pressure during inspiration raised survival from 21 to 84 %, and in Copenhagen in 1952 positive pressure given by hand with a bag through a tracheostomy substantially reduced deaths from acute polio [4].

The question of which variable to hold became a question of injury. In mechanically ventilated rats, high airway pressure at a normal tidal volume left the lungs like those of controls while a high tidal volume produced permeability edema even at low airway pressure, and 10 cmH_2O of PEEP markedly reduced it [15]. The ARDS Network trial turned the volume into the setting to limit, measuring the plateau after a 0.5 s pause at the end of inspiration [2], the driving pressure then emerged as the variable that best stratified risk [3], and lung-protective strategies built on that understanding of ventilator-induced injury have markedly improved outcomes [1].

The patient's side of the cycle has a literature of its own. In 62 patients who triggered every breath, 15 had an asynchrony index above 10 % of their efforts, ineffective triggering and double triggering were the main patterns, and patients with frequent asynchrony stayed on the ventilator for a median of 25.5 days against 7.5 [9]. A mathematical model of pressure support showed that the flow at the end of the patient's neural inspiration, relative to the peak flow, depends mostly on the ratio of the respiratory time constant to the neural inspiratory time, so that any single fixed flow criterion for ending a breath ends some breaths early and others late [16]. Auto-PEEP, the trapped pressure of an expiration cut short, was brought to clinical attention about 30 years before a review of 2011 listed its effects on hemodynamics, work of breathing, synchrony and the monitoring of mechanics [17]. The mechanics themselves can be fitted by least squares. In paralyzed patients the fit came close to the occlusion values, while under pressure support with a low support level and strong muscle activity it underestimated the resistance by 10.4 $cmH_2O \cdot s/L$ and overestimated the compliance by 35.2 mL/cmH_2O on average [18]. The control-engineering literature has since posed the pressure servo as an adaptive problem, tracking a time-varying target pressure for unknown patient, hose and leak parameters in the presence of effort, with a proof of stability [8]. None of these sources can set the true lung, effort and leak beside each breath the machine reported, and that pairing is what the simulator keeps.

4.3 A Lung Behind a Wye

The simulated ventilator is a blower held at P_b behind a proportional inspiratory valve, a circuit of compliance C_t whose pressure P is read at the wye, and an expiratory valve that vents the circuit to the room, as shown in Figure 4.1. Beyond the wye a leak, an airway resistance R and a single compartment of compliance C make up the patient, whose respiratory muscles add a pressure $P_{mus}(t)$.

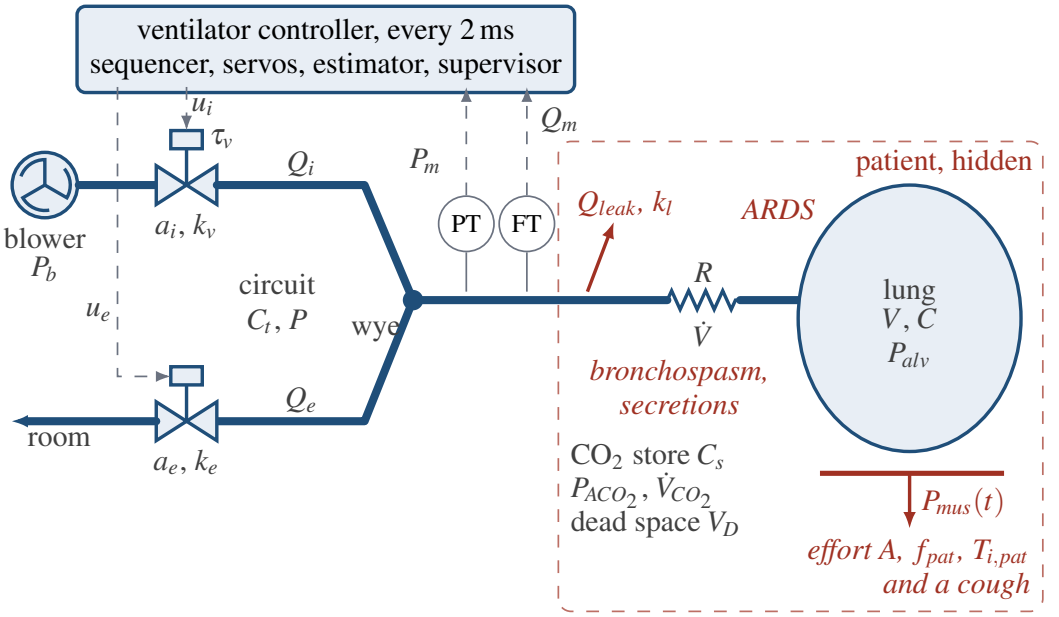


Figure 4.1 The ventilator circuit and the patient behind the wye. The blower holds P_b behind the inspiratory valve of opening a_i and coefficient k_v, the circuit of compliance C_t at pressure P joins the expiratory valve (a_e, k_e) at the wye, and each valve follows its command u_i or u_e through the lag τ_v. The pressure and flow transmitters PT and FT at the wye supply the only measurements P_m and Q_m. Everything in the dashed box is hidden from the controller: the leak Q_{leak} of coefficient k_l past the sensor, the airway resistance R carrying $\dot{V}$, the lung of volume V, compliance C and alveolar pressure P_{alv}, the muscle pressure P_{mus} set by the effort A, rate f_{pat} and neural time $T_{i,pat}$, and the CO_2 store. The disturbances, drawn in red with their text labels in italics, are the leak, bronchospasm and secretions on R, the ARDS stiffening of C, and the effort with its cough.

The five integrated states are the lung volume V above its relaxed volume, the circuit pressure P, the two valve openings a_i and a_e, and the alveolar CO_2 partial pressure P_{ACO_2}. The derivative function stays pure, and everything discrete, the effort schedule, the disease ramps, the breath record and the audit, moves only between integration steps. The signals are classified in Table 4.1.

4.3.1 The Patient

The lung is a single compartment, as in Section 1.4.2, holding gas behind a resistance. Its equation of motion includes the patient's effort, as shown in Equation (4.1).

$$P_{alv} = \frac{V}{C} - P_{mus}(t), \qquad \dot{V} = \frac{P - P_{alv}}{R} \tag{4.1}$$

where P_{alv} is the alveolar pressure and $\dot{V}$ the flow into the lung, so that at the airway $P = R\dot{V} + V/C - P_{mus}$. The shipped patient has $R = 10\,\mathrm{cmH_2O \cdot s/L}$ and $C = 50\,\mathrm{mL/cmH_2O}$, a time constant RC of 0.5 s, and both are the slider values times multipliers that the disease events ramp linearly, the compliance to half over 60 min for ARDS and the resistance to double over 60 s for bronchospasm. Secretions multiply R by $\exp(\sigma_s x_k)$, where x_k is a seeded first-order random sequence with a 3 s time constant updated every 10 ms and σ_s is the slider as a fraction. The effort is one half-sine per breath

Table 4.1 Signals of the Ventilator and the Patient, With Their Defaults

Symbol	Role	Default	Range
V	state, lung volume above relaxation	C·PEEP	—
P	state, circuit pressure	PEEP	—
a_i, a_e	states, valve openings	pass Q_{bias}	0–1
P_{ACO_2}	state, alveolar CO_2	40 mmHg	—
u_i, u_e	MVs, valve commands	—	0–1
P_m	measured, CV of the pressure and PEEP servos	—	—
Q_m	measured, CV of the flow servo	—	—
$\hat{V}_T$	estimated, CV of the volume loop	—	—
ΔP	MV of the volume loop, support	10 cmH_2O	0–40
C	DV, compliance (ARDS ramp)	50 mL/cmH_2O	10–100
R	DV, resistance (bronchospasm)	10 $cmH_2O \cdot$ s/L	3–60
Q_{leak}	DV, leak at 10 cmH_2O	0	0–400 L/min
A	DV, peak effort	0	0–15 cmH_2O
f_{pat}, $T_{i,pat}$	DV, patient's rate, neural time	18 min^{-1}, 1.0 s	6–40, 0.4–2
—	DV, secretions (noise on R)	0 %	0–50
P_{alv}, P_{mus}	hidden truth	—	—

the patient takes, as shown in Equation (4.2).

$$\begin{aligned} P_{mus}(t) &= A \sin\left(\frac{\pi(t-t_k)}{T_{i,pat}}\right), \qquad t_k \le t < t_k + T_{i,pat} \\ t_{k+1} &= t_k + \frac{60}{f_{pat}}\,(1+\varepsilon_k) \end{aligned} \tag{4.2}$$

where A is the peak effort, $T_{i,pat}$ the neural inspiratory time, capped at 80 % of the period, f_{pat} the patient's rate per minute and ε_k a seeded uniform jitter of ± 6 %. A change of effort, rate or neural time applies from the next effort. A cough is an expiratory half-sine of 40 cmH_2O over 0.4 s, subtracted from P_{mus}.

4.3.2 The Circuit and Its Valves

The circuit between the valves and the wye stores gas in its compliance, and the valves and the leak are orifices, as shown in Equation (4.3).

$$\begin{aligned} C_t \dot{P} &= Q_i - Q_e - Q_{leak} - \dot{V} \\ Q_i &= a_i k_v\, \psi(P_b - P), \qquad Q_e = a_e k_e\, \psi(P) \\ Q_{leak} &= k_l\, \psi(P), \qquad \tau_v \dot{a} = u - a \\ \psi(\Delta p) &= \frac{\Delta p}{\sqrt{|\Delta p| + P_L}} \end{aligned} \tag{4.3}$$

where ψ is the square-root orifice law smoothed below $P_L = 0.1$ cmH_2O so that its slope stays finite at zero, Q_i is zero when $P \ge P_b$ and Q_e zero when $P \le 0$, so neither valve passes gas backward, and both openings are clipped to $[0, 1]$ after each step. Each coefficient is set from a stated flow through the same ψ, so the inspiratory valve passes exactly 180 L/min fully open into an open airway and the expiratory valve 120 L/min fully open at 5 cmH_2O, and the leak is entered as its flow at 10 cmH_2O. A disconnect adds an orifice of 400 L/min at 1 cmH_2O. The leak sits on the patient's side of the flow sensor, so the sensor reads $\dot{V} + Q_{leak}$.

Table 4.2 Model Constants. Class V Is a Slider in the Show Model Dialog and C a Constant in the Code. Nothing in This Model Is Flagged Hidden, but the Patient's Values Never Reach the Controller

Symbol	Meaning	Value	Class
P_b	blower pressure	60 cmH_2O (30–80)	V
$Q_{i,max}$	inspiratory valve fully open, open airway	180 L/min	V
$Q_{e,5}$	expiratory valve fully open at 5 cmH_2O	120 L/min	V
C_t	circuit compliance	1.5 mL/cmH_2O (0.3–4)	V
τ_v	valve response time	5 ms (1–30)	V
Q_{bias}	base flow above the flow trigger	1.5 L/min	V
T_{lock}	trigger lockout after inspiration	0.25 s	V
$T_{i,max}$	longest pressure-support breath	2.5 s	V
PBW	predicted body weight	70 kg	V
V_D	dead space	150 mL	V
$\dot{V}_{CO_2}$, C_s	CO_2 production, store	200 mL/min, 45 mL/mmHg	V
σ_P, σ_Q	sensor noise (1σ)	0.05 cmH_2O, 0.3 L/min	V
P_L	orifice smoothing pressure	0.1 cmH_2O	C
K	alveolar CO_2 constant	0.863	C
—	effort jitter, smallest effort	±6 %, 0.5 cmH_2O	C
—	cough	40 cmH_2O, 0.4 s	C
—	disconnect orifice	400 L/min at 1 cmH_2O	C

4.3.3 Carbon Dioxide

Carbon dioxide is one store, a slow outcome signal rather than a model of gas exchange, as shown in Equation (4.4).

$$C_s \dot{P}_{ACO_2} = \dot{V}_{CO_2} - \dot{V}_A \frac{P_{ACO_2}}{K}, \qquad \dot{V}_A = \frac{(V_T - V_D)^+}{T_b} \tag{4.4}$$

where $K = 0.863$ mmHg per (mL/min)/(L/min), V_T is the true tidal volume of the last finished breath, T_b its duration and V_D the dead space, and $\dot{V}_A$ falls to zero after 15 s without a breath. With the defaults of Table 4.2, 420 mL at 16 min^{-1} settles at 39.95 mmHg, and apnea raises the CO_2 by 4.44 mmHg a minute.

4.3.4 Initial State and Numerics

Every case starts with the lung at rest at PEEP, $V = C \cdot \text{PEEP}$ and $P = \text{PEEP}$, the valves at the openings that pass Q_{bias} in automatic mode or at the operator's stations in manual mode, and the CO_2 at 40 mmHg. The engine of Section 1.6.1 carries the five states forward with a fourth-order Runge-Kutta step of 1 ms. The circuit is the stiff part. With both valves shut its time constant $C_t R$ is 15 ms on the shipped patient, and with the expiratory valve wide open at 1 cmH_2O it falls to 2.6 ms, so before each step the integrator computes the node's conductance G and takes $\min(48, \lceil \Delta t\, G / 0.8 C_t \rceil)$ sub-steps, almost always one. The controller and sensors run every 2 ms, a historian row is written every 0.2 s, enough for trends that change once a breath, and the scene draws its waveforms from a 100 Hz buffer of its own. The patient's jitter, the secretions and the sensor noise come from the engine's generators, seeded at 20261007. Halving the step moves the true tidal volume and plateau of the passive cases by at most 0.24 % and the tidal volume of the leak case by 0.50 %, and the application passes its 37 verification checks.

4.3.5 Assumptions

One compartment. The lungs and chest wall are a linear resistance and a linear compliance. Real lungs are many compartments with their own time constants, recruit and derecruit with PEEP and stiffen at high volume, so the passive pressure-volume loop here is straight where a real one bends.

A scripted patient. The effort is a half-sine with jitter and no chemical drive. The patient does not breathe harder when the CO_2 rises or less when the support is generous, and coughs are events.

An idealized machine. The blower holds its pressure at any flow, the valve laws are exact and known to the controller, the circuit has compliance but no resistance, and the only sensors are at the

wye, with Gaussian noise and no drift. There is no sensor at the valves, no compensation for tubing compliance and no trigger filter beyond a 10 ms lag.

An orifice leak. The leak coefficient is fixed, while a real mask leak changes with pressure, posture and fit.

Carbon dioxide only. One store with fixed production and dead space stands in for gas exchange, and oxygenation is not modeled.

A truth audit. Efforts are classified against the hidden P_{mus}, which a ventilator could only infer from its waveforms or from an esophageal balloon, using the classes of the asynchrony literature [9] with simple timing rules.

Teaching values. The 6 mL/kg target and the 30 cmH_2O plateau follow the ARDS Network values [2], the application draws a 15 cmH_2O driving-pressure line that its documentation attributes to the driving-pressure analysis [3], and the 40 cmH_2O high-pressure limit, the alarm settings and the challenge criteria are chosen for teaching. Real settings and alarm limits come from the unit's protocol, the clinician and the device's conformity to its standard [10].

4.4 What the Equations Promise

Four closed forms describe what a mode can hold, and each is checked against the engine.

4.4.1 Holding the Volume or the Pressure

Volume control imposes the flow and leaves the pressure free, so after a pause long enough for the flow to stop the plateau is the recoil of the delivered volume, and pressure control imposes the pressure and leaves the volume to the lung's time constant, as shown in Equation (4.5).

$$P_{plat} = \mathrm{PEEP} + \frac{V_T}{C}, \qquad V_T = C\,\Delta P\left(1 - \mathrm{e}^{-(T_i - T_r/2)/RC}\right) \tag{4.5}$$

where ΔP is the pressure above PEEP, T_i the inspiratory time and T_r the rise time, half of which the half-cosine rise of Section 4.5 costs the lung. At a PEEP of 8 cmH_2O and 420 mL, the plateau is 16.40 cmH_2O at 50 mL/cmH_2O and 31.33 cmH_2O at 18 mL/cmH_2O, and the engine gives 16.4 to 16.5 and 31.3 to 31.5 cmH_2O. At 10 cmH_2O for 1 s with a 0.1 s rise, the volume is 425.2 mL at 50 mL/cmH_2O and 179.1 mL at 18 mL/cmH_2O, against 424 and 179 mL on the engine. A mode is a choice of which side of the first expression the machine guarantees.

Pause. Try Exercise 4.1 before reading on.

4.4.2 Expiration That Does Not Finish

A passive lung empties toward PEEP with the time constant RC. When each expiration lasts T_e, volume control adds V_T per breath and the trapped volume settles where each expiration removes what each breath adds, as shown in Equation (4.6).

$$\mathrm{PEEP}_i = \frac{V_T}{C}\,\frac{\mathrm{e}^{-x}}{1-\mathrm{e}^{-x}}, \qquad x = \frac{T_e}{RC} \tag{4.6}$$

In case 6 after the spasm, $R = 20\,cmH_2O\cdot s/L$ and $C = 50\,mL/cmH_2O$ give $RC = 1.00$ s, and 1.50 s of expiration gives 2.42 cmH_2O for the volume the engine delivers in this case, slightly above the 420 mL setting. The engine measures 2.58, and with the rate of case 6 swept from 34 down to 10 min^{-1}, Figure 4.2(a), it stays 5 to 8 % above the closed form at every x from 0.77 to 5. The difference is the start of each expiration, since a fit of the alveolar decay over the rest of it returns a time constant of 1.000 s, RC itself. Volume control without a pause ends inspiration at the 24.4 cmH_2O peak, and the airway takes about 0.12 s to come down to PEEP while the expiratory servo discharges the circuit, an excess of 0.54 $cmH_2O\cdot s$ that slows the first part of every expiration and leaves 0.16 cmH_2O more trapped at the case's rate. Only x moves the trapped pressure. PEEP does not appear in Equation (4.6).

Pause. Try Exercise 4.2 before reading on.

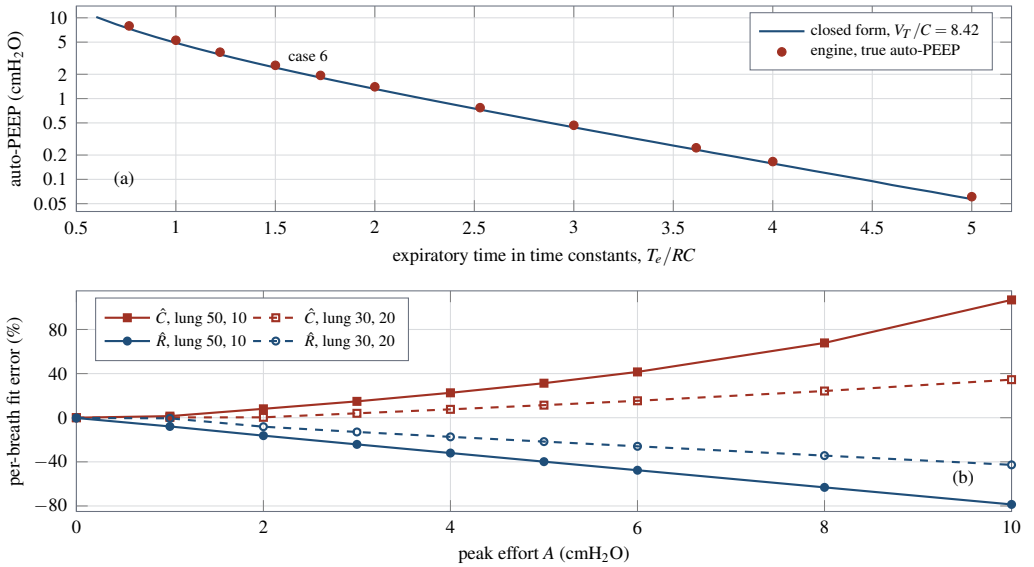


Figure 4.2 Two characteristics of the plant, measured on the engine. (a) True auto-PEEP in volume control in case 6 after the spasm ($R = 20\,\mathrm{cmH_2O \cdot s/L}$, $C = 50\,\mathrm{mL/cmH_2O}$, 1.0 s inspiration, no pause), with the rate set from 10 to 34 $\mathrm{min^{-1}}$, against the expiratory time in time constants, beside Equation (4.6). (b) Error of the per-breath least-squares resistance and compliance against the peak of the patient's effort, over 90 s of assist-controlled volume breaths at 16 $\mathrm{min^{-1}}$ with efforts at 18 $\mathrm{min^{-1}}$, in a model run of case 7 without its scripted events, on the shipped lung (50 $\mathrm{mL/cmH_2O}$, 10 $\mathrm{cmH_2O \cdot s/L}$) and on the lung case 7 ends with (30 $\mathrm{mL/cmH_2O}$, 20 $\mathrm{cmH_2O \cdot s/L}$).

4.4.3 What the Wye Sees

The flow sensor reads $Q_m = \dot{V} + Q_{leak}$ plus noise. A flow trigger fires when this flow, less the leak the estimator believes in, passes its threshold after the lockout, and pressure support ends a breath when the flow falls to a fraction of its peak. A leak that nobody has subtracted starts breaths and keeps them from ending. With 14 L/min of leak at a PEEP of 10 $\mathrm{cmH_2O}$, the filtered wye flow passes a 2 L/min trigger once the lung's own expiratory flow has fallen to 10.4 to 11.1 L/min, which between minutes 31 and 39 of the challenge comes 0.44 to 0.48 s into each expiration, 1.23 to 1.35 time constants of its lung. An effort enters the same flow, so a cycle-off fraction reads the sum of the support and the patient's pull, and the time constant relative to the neural time decides which breaths a fixed fraction ends early [16].

4.4.4 The Edge of the Actuator

Only the inspiratory valve can add gas, a one-sided actuator in the sense of Section 1.4.6, so against a leak the circuit pressure cannot exceed the point where the fully open valve's flow equals the leak's, $k_v \psi(P_b - P) = k_l \psi(P)$. At a PEEP of 8 $\mathrm{cmH_2O}$ the fully open valve passes 168 L/min, while a leak of 300 L/min at 10 $\mathrm{cmH_2O}$ would take 268 L/min, so the pressure falls until the two balance at 3.46 $\mathrm{cmH_2O}$. The same balance at 8 $\mathrm{cmH_2O}$ allows a leak of 187.6 L/min, and the engine holds PEEP to within 0.02 $\mathrm{cmH_2O}$ up to 187 L/min and lets it sag from 188 L/min. Ventilation is lost much earlier. With pressure control at 10 $\mathrm{cmH_2O}$ above PEEP, a 150 L/min leak leaves a breath of 123 mL at a peak airway pressure of 11.1 $\mathrm{cmH_2O}$, and 180 L/min leaves 21 mL.

4.4.5 Effort as an Unmodeled Input

The least-squares fit of Section 4.5 explains the measured pressure with R, $1/C$ and a starting pressure, and the effort is a pressure it cannot see. A patient who triggers each breath puts the effort into the

Table 4.3 Controller Settings, Defaults and Ranges

Symbol	Setting	Default	Range
—	mode	VC	VC, PC, PS
f	rate, backup rate in PS	16 min^{-1}	4–40
T_i, T_p	inspiratory time, pause (VC)	1.0 s, 0.2 s	0.3–3, 0–1
V_T^*	tidal volume, target	420 mL	100–900
ΔP	pressure above PEEP (PC, PS)	10 cmH_2O	0–40
PEEP	end-expiratory pressure	5 cmH_2O	0–20
$\dot{V}_{trig}$	flow trigger	2 L/min	0.5–15
ΔP_{trig}	pressure trigger, below PEEP	2 cmH_2O	0.5–10
f_{cyc}	cycle-off, of peak flow	25 %	5–70
T_r	rise time	0.1 s	0.02–0.5
—	VC profile	square	or decelerating
$K_{c,P}$, $\tau_{I,P}$	pressure servo	4, 60 ms	0.1–20, 2–500
$K_{c,Q}$, $\tau_{I,Q}$	flow servo	2, 30 ms	0.05–6, 2–500
$K_{c,E}$, $\tau_{I,E}$	PEEP servo	10, 30 ms	0.5–50, 2–500
—	leak compensation, adaptive	off, off	on, off
K_V	volume step, of the error	0.6	0.1–1.5
—	trigger, learn from machine breaths only	flow, off	pressure, on
—	protective layer	off	on, off
$P_{plat,max}$	plateau cap	30 cmH_2O	20–40
$V_{T,max}$	volume cap, per kg	8 mL/kg	4–12
P_{high}	high-pressure limit	40 cmH_2O	20–60
α	weight of the newest fit	0.5	0.05–1

Servo gains in % of valve opening per cmH_2O, or per L/min for the flow servo.

same phase of every breath, so the error is systematic rather than random, as shown in Figure 4.2(b), a counterfactual model run of case 7's settings with its scripted events removed. On the shipped lung each 1 cmH_2O of effort costs about 8 percentage points of resistance, from -0.24 to -78.6 % at 10 cmH_2O, while the compliance error grows faster than linearly to $+107$ %. On the lung case 7 ends with, the same 5 cmH_2O effort gives -21.65 and $+11.40$ %, because there a 420 mL breath needs 14.0 cmH_2O of elastic pressure against 8.4 and about twice the resistive pressure, so the effort is a smaller share of what the fit explains. On that lung a 1 cmH_2O effort never triggers, lands at random phases and leaves the fit within -4.6 to $+3.0$ % of the resistance. The same dependence on the effort's share of the pressure appeared in patients, whose fitted mechanics became satisfactory once a higher support level had reduced their muscle activity [18]. The fit faces the problem of dividing credit between inputs that move together, which Volume 1, Chapter 12 treats on recorded plant data.

🕮 **Pause.** Try Exercise 4.3 before reading on.

4.5 The Ventilator's Loops

Every 2 ms the controller reads P_m and Q_m, each with seeded Gaussian noise, and nothing else about the patient. In that period it accumulates the sample into the breath under way, steps the breath sequencer, which at the end of a breath has the estimator fit it and the supervisor update the volume loop and the caps, then runs the valve servos and finally the alarms. The settings are listed in Table 4.3.

4.5.1 The Breath Sequencer

The sequencer is a state machine over expiration, inspiration, the volume-control pause and two hold maneuvers. Expiration ends on a patient trigger once the lockout T_{lock} after inspiration has passed, when the wye flow less the estimated leak, filtered over 10 ms, exceeds $\dot{V}_{trig}$ or the airway pressure falls ΔP_{trig} below PEEP, or on the clock when a breath at the rate f falls due. In volume control the flow follows a square or decelerating profile for $T_i - T_p$ and the pause holds both valves shut. A pressure breath follows the target of Equation (4.7) for T_i in pressure control, and in pressure support it is cycled off once at least 0.15 s and half the rise have passed and the filtered flow falls below f_{cyc} of its peak, or at $T_{i,max}$. Any breath ends at once above P_{high}. The delivery of a breath is fixed when

it starts, so a setting moved mid-breath applies to the next one. When a volume-control breath has a pause, its square profile delivers $Q = V_T/(T_i - T_p + \tau_v + C_t\hat{R})$, because after the flow phase the valve still delivers for its response time and the circuit, charged to the resistive pressure, empties into the lung during the pause, 20 ms of extra flow time on the shipped patient. There is no separate synchronized intermittent mandatory mode, since pressure support with a backup rate covers its lessons.

4.5.2 Three Servos on One PID

All three servos are instances of the velocity-form PID of Section 1.6.2, Equations (1.12) to (1.15), which clamps only its emitted output and lets the integral alone absorb the clamp by back-calculation with $T_t = \tau_I$. They execute every $\Delta t_c = 2\,\text{ms}$, with no derivative action and no rate limit, and both inspiratory servos are reset to zero at the start of every breath. The action $\mathscr{A}$, the a of Equation (1.12), is $+1$ for the two inspiratory servos, whose valve raises the pressure or the flow it controls, and -1 for the PEEP servo, since more expiratory opening lowers the pressure. Each servo adds its output to a feedforward u_{ff} that inverts the valve's own law of Equation (4.3), the opening that would pass a demanded flow $\hat{Q}$ at the measured pressure, and its clamp is $[-u_{ff}, 1-u_{ff}]$ so that the total stays within the valve. The pressure target of a pressure breath and the demand of each servo are given by Equation (4.7).

$$\begin{aligned} P_{sp}(\tau) &= \text{PEEP} + \tfrac{1}{2}\Delta P\big(1-\cos(\pi\tau/T_r)\big), \quad \tau < T_r \\ \hat{Q}_{PC,PS} &= (Q_m + \tau_v\dot{Q}_m)^+ + C_t\dot{P}_{sp} \\ \hat{Q}_{VC} &= Q_{prof}(\tau) + \hat{Q}_{leak} \\ \hat{Q}_E &= \big(u_i k_v \psi(P_b - P_m) - Q_m\big)^+ \end{aligned} \tag{4.7}$$

where $\dot{Q}_m$ is the measured flow's derivative filtered over 6 ms, Q_{prof} the volume-control profile, $\hat{Q}_{leak} = \hat{k}_l\,\psi(P_m)$ the estimated leak when compensation is on and $\hat{Q}_E$ the flow the expiratory valve must shed. The pressure servo holds its integral, $\tau_I = \infty$, until the rise has ended, because integrating the designed lag behind a moving target holds the valve open past it. The PEEP servo tracks the valve whenever it is not in charge, so that it takes over without a bump. In expiration the inspiratory valve passes a base flow of $Q_{bias} + \dot{V}_{trig}$, Q_{bias} alone with a pressure trigger, plus with compensation the estimated leak at the larger of P_m and PEEP. The bias sits above the trigger because a fixed base flow below the threshold could never let a patient trigger, and the expiratory valve, which can only let gas out, holds PEEP against a leak only with this flow from the other side.

On a passive lung, a 15 cmH_2O step from a PEEP of 5 cmH_2O in 0.1 s overshoots by at most 0.77 cmH_2O over R from 5 to 40 $\text{cmH}_2\text{O}\cdot\text{s/L}$ and C from 20 to 80 $\text{mL/cmH}_2\text{O}$, rising from 10 to 90 % in 54 to 67 ms, measured on the second breath of case 3 with the PEEP, the lung and the timing set before Run, so that the lung starts at rest at the new PEEP. Two copies of the controller changed in one place each show what the design buys. A straight-line rise overshoots by at most 0.61 cmH_2O but takes 76 to 82 ms, and letting the integral run during the rise raises the worst overshoot to 1.26 cmH_2O, past the 1.0 cmH_2O that the application's own check allows.

4.5.3 Identification From Every Breath

The estimator identifies the individual lung, the role Section 1.4.4 gives to measurement in a living plant. Over each whole breath it fits the passive equation of motion by least squares, as shown in Equation (4.8).

$$\begin{aligned} &\min_{R,C,P_0} \sum_k \left(P_m(t_k) - R\hat{V}(t_k) - \frac{\hat{V}(t_k)}{C} - P_0\right)^2 \\ &\hat{V} = Q_m - \hat{k}_l\,\psi(P_m), \qquad \widehat{\text{PEEP}}_i = P_0 - P_{ee} \\ &\hat{k}_l = \frac{\int Q_m\,\mathrm{d}t}{\int \psi(P_m)\,\mathrm{d}t} \end{aligned} \tag{4.8}$$

where $\hat{V}$ integrates $\hat{V}$ from the start of the breath, P_0 is the alveolar pressure the breath started from and P_{ee} the measured end-expiratory pressure, filtered through 25 ms during expiration. The normal equations are summed every 2 ms and solved when the next breath starts, and a fit counts only with at least 50 samples, a breath longer than 0.8 s, more than 50 mL, R between 0.2 and 300 $\mathrm{cmH_2O \cdot s/L}$ and an elastance between 2 and 500 $\mathrm{cmH_2O/L}$. The smoothed $\hat{R}$, $\hat{C}$ and auto-PEEP weigh the newest fit by $\alpha = 0.5$, and an option lets them learn only from breaths the machine triggered. The leak coefficient $\hat{k}_l$ uses the whole breath, since a lung that ends where it began adds no net flow, and it weighs the newest breath by 0.8. In the shipped challenge it reads 13.8 to 14.1 L/min on every breath between minutes 31 and 39 for the true 14 L/min, auto-triggers and all, but once the patient's efforts fall at different points of each machine breath the premise fails and the per-breath value swings from 9.2 to 20.7 L/min around a mean of 14.2, which is why the monitor reads 11.2 L/min at minute 45. Holds shut both valves, for 0.6 s at the end of inspiration to read the plateau over the last 0.1 s, or for 1.0 s before the next breath to read the total PEEP over the last 0.2 s.

4.5.4 The Volume Loop and the Protective Layer

With adaptive support on, in pressure control or pressure support, the shared PID runs once per breath as a discrete integrator on the measured volume, as shown in Equation (4.9).

$$\begin{aligned} \Delta P_{k+1} &= \Delta P_k + \frac{K_V}{\hat{C}\hat{\eta}} \left(V_T^* - \hat{V}_{T,k}\right) \\ \hat{\eta}_{PC} &= 1 - \mathrm{e}^{-(T_i - T_r/2)/\hat{R}\hat{C}}, \qquad \hat{\eta}_{PS} = 1 - f_{cyc} \end{aligned} \tag{4.9}$$

where $\hat{C}\hat{\eta}$, with $\hat{\eta}$ clipped to $[0.3, 1]$, is the volume one more $\mathrm{cmH_2O}$ would buy, so that $K_V = 1$ would remove the whole error in one breath. The step is limited to 3 $\mathrm{cmH_2O}$ per breath by the PID's slew limit, the support stays between 2 $\mathrm{cmH_2O}$ and the protective cap, or 60 $\mathrm{cmH_2O}$ with the layer off, and the loop freezes its output while the leak estimate moves by more than 3 L/min at 10 $\mathrm{cmH_2O}$ between breaths, because until a new leak is learned the measured volume carries the part not yet subtracted. With the loop off, the PID tracks the operator's setting, so switching on is bumpless. The protective layer caps each breath before it starts. In volume control the volume is limited to the setting, to $V_{T,max}$ times the predicted body weight and to $\hat{C}(P_{plat,max} - \mathrm{PEEP} - \widehat{\mathrm{PEEP}}_i)$, and in the pressure modes ΔP is limited to $P_{plat,max} - \mathrm{PEEP} - \widehat{\mathrm{PEEP}}_i$ and a breath is cycled off once its volume reaches $V_{T,max}$.

4.5.5 Alarms, Manual Mode and the Three Models

The ventilator's alarms come from its own measurements. DISCONNECT, HIGH PRESSURE and PEEP NOT HELD, the last after 1.5 s more than 2 $\mathrm{cmH_2O}$ below PEEP in expiration, are alarms, and LEAK above 10 L/min at 10 $\mathrm{cmH_2O}$, AUTO-PEEP above 2 $\mathrm{cmH_2O}$, LOW TIDAL VOLUME below 75 % of the target and APNEA BACKUP are warnings. ASYNCHRONY comes from the truth audit, which counts an effort that starts in expiration and starts no breath within 0.1 s of its end as missed, a patient trigger outside any effort as an auto-trigger and a second trigger inside one effort as a double, ignoring efforts below 0.5 $\mathrm{cmH_2O}$. Manual mode hands both valves to the operator as a bag with no PEEP valve, a squeeze being an inspiration, while the PEEP servo tracks the hand. The return to automatic mode starts the cycle in expiration: the inspiratory valve takes the base flow at once, and the PEEP servo takes the expiratory valve over from where the hand left it.

The simulation model is Equations (4.1) to (4.4). The control models are the closed forms of Section 4.4, a first-order lung behind a valve whose law is known. The controller's internal models are the inverted valve laws of the feedforwards, the passive equation of motion that the estimator fits, the orifice law it assumes for the leak, and the gain $\hat{C}\hat{\eta}$ of the volume loop. None of them contains the effort.

Table 4.4 The Nine Cases and the Challenge

#	Change from the reference line	Teaching point
1	manual, 1 s squeeze every 5 s, C to 20 at 30 s	the bag
2	VC, PEEP 8, 15 min^{-1}, C 50 to 18 at 30 s	the plateau pays
3	PC as case 2	the volume pays
4	PS 8, effort 6 at 18 min^{-1}, backup 10 min^{-1}	triggering, cycling
5	case 4 with effort 5 at 15, 30 L/min leak at 20 s	a leak
6	VC at 24 min^{-1}, no pause, bronchospasm at 20 s	auto-PEEP
7	holds at 20 and 25, C 30 at 40, spasm at 80, effort 5 at 160 s	identification
8	PS, 15 L/min trigger, then 0.5 L/min and a 2 L/min leak, then VC 0.6 s	asynchrony
9	PC, PEEP 8, compensation, 300 L/min leak at 20 s	honest infeasibility
10	60 min: ARDS ramp, 14 L/min leak at 30, patient at 40	challenge

Table 4.5 Measured Outcomes of the Cases

Case and configuration	Result
1, 50 mL/cmH_2O and 20 mL/cmH_2O	422–423 and 384 mL, peaks 12.6–12.7 and 22.7–22.8 cmH_2O
2, as shipped	419 to 423 mL, plateau from 16.4–16.5 to 31.3–31.5 cmH_2O
2, protective layer	six breaths of 420–423 mL at 31.4–31.5 cmH_2O, then 395–396 mL at 29.9–30.0 cmH_2O
3, as shipped	424 to 179 mL, plateau 17.9 to 18.0 cmH_2O
3, adaptive, then with the layer	420 mL at 31.3 cmH_2O, then 393–394 mL at 29.9 cmH_2O
4, cycle-off 25, 5, 50 %	0.73–0.74, 0.84, 0.60 s against 1.00 s
5, no compensation	11 auto-triggers, 2.50 s breaths, 103 to 414 mL
5, compensation	2 auto-triggers, 0.68 to 0.77 s, 454 to 462 mL
6, 24 min^{-1}, 18, 14	auto-PEEP 2.58, 0.96, 0.35 cmH_2O
7, passive, then effort 5	$\hat{R}$, $\hat{C}$ within 0.5 and 0.2 %, then −21.6 to −21.8 and +10.8 to +12.0 %
8, three parts	8 of 14 missed, 13 of 14 auto, 13 of 14 double
9, 300 L/min leak	3.45 to 3.46 cmH_2O, valve open, no breath
10, shipped, suggested	27.34 and 99.74 % in band

4.6 Nine Cases and an Hour

Table 4.4 lists the cases. Each starts from the reference line of Tables 4.2 and 4.3 on the passive shipped patient and changes it as its row says. Every number below comes from a run of the engine without the interface at the default seed, stepped as the browser steps it (Section 1.6.1). A setting is changed at $t = 0$ before Run unless a Reset is named, which restarts the case with the learner's settings kept. All volumes, plateaus and auto-PEEP values are true values from the hidden record unless they are called measured. The outcomes are collected in Table 4.5.

4.6.1 The Bag

Case 1 runs in manual mode with the inspiratory valve opened to 16 % for 1 s every 5 s and the expiratory valve shut during each squeeze. Into the shipped lung each squeeze delivers 422 to 423 mL at a peak of 12.6 to 12.7 cmH_2O. At 30 s the lung stiffens to 20 mL/cmH_2O, and the same squeeze delivers 384 mL, 9 % less, at 22.7 to 22.8 cmH_2O, 1.8 times the pressure, because the gas comes through a valve from a source of fixed pressure and the flow falls as the airway pressure climbs toward it. With no PEEP valve the lung empties to atmospheric pressure after each release.

4.6.2 Which Variable to Hold

Case 2 delivers 420 mL fifteen times a minute in volume control at a PEEP of 8 cmH_2O while the lung stiffens from 50 to 18 mL/cmH_2O at 30 s. The volume stays at 419 to 423 mL and the pressure pays for it. The plateau read in the pause climbs from 16.4 or 16.5 to between 31.3 and 31.5 cmH_2O, the peak from 21.3 or 21.4 to between 35.8 and 36.2 cmH_2O, and the driving pressure reaches 23.3 to 23.5 cmH_2O. With the protective layer on, the six breaths after the step still deliver 420 to 423 mL at

31.4 to 31.5 cmH_2O, because the layer caps on the identified compliance and the smoothed estimate moves only halfway to each new fit. Trimming starts at 56.5 s, by 72.5 s the layer caps the volume at 396 mL, and from then on breaths of 395 to 396 mL hold the plateau at 29.9 to 30.0 cmH_2O. Ten minutes in, the cost is 44.0 mmHg of CO_2 against 41.7 mmHg unprotected.

> **TRY IT IN THE APP** **2 · Volume Control and a Stiffening Lung**
>
> Load scenario 2 and press Run on the Loops view. At 30 s the lung stiffens from 50 to 18 mL/cmH_2O. Watch the plateau badge: the volume stays at 419 to 423 mL while the plateau climbs from 16.4 or 16.5 to between 31.3 and 31.5 cmH_2O, past the dashed 30 cmH_2O limit.

Case 3 holds 10 cmH_2O above the same PEEP. The plateau stays at 17.9 to 18.0 cmH_2O and the volume falls from 424 to 179 mL. With adaptive support the first breath after the step is still 177 mL, the next five are 231, 285, 339, 380 and 402 mL, the first three each limited to 3 cmH_2O of new support and so about 54 mL apart at 18 mL/cmH_2O, and by the tenth the volume is 420 mL at 23.4 cmH_2O of support and a plateau of 31.3 cmH_2O, as in volume control. With the protective layer as well, the support stops at 22.0 cmH_2O, the plateau limit less PEEP, and the breath settles at 393 to 394 mL under a plateau of 29.9 cmH_2O. Adaptive pressure control and volume control end in the same place, and the layer is the ceiling over both.

4.6.3 A Patient Who Breathes

In case 4 the patient pulls 6 cmH_2O for about 1 s eighteen times a minute on pressure support of 8 cmH_2O, every effort triggers a breath, and the volume is 482 to 486 mL. The machine ends each breath when the flow falls to 25 % of its peak, after 0.73 to 0.74 s, while the patient pulls for 1.00 s. A cycle-off of 5 % stretches the breath to 0.84 s and 50 % cuts it to 0.60 to 0.61 s, and neither matches the patient, because the flow the machine reads carries the effort and the support together. A low ratio of time constant to neural time, 0.5 here, is the condition under which a fixed fraction ends breaths early [16]. Support levels of 4 and 14 cmH_2O give 333 to 335 and 705 to 712 mL. The estimator, which assumes a passive lung, reads this patient's compliance as 89.9 against a true 50 mL/cmH_2O.

> **HISTORY** **The Synchrony Problem of 1929**
>
> The tank respirator's authors set its rate and pressures by hand, watching a water manometer, and found that a breathing subject does not simply follow the machine. As they raised the pressure, a subject fell into rhythm with the pump at about 5 to 10 cmH_2O and stayed in rhythm at any higher pressure. One man of normal physique needed 18 to 20 cmH_2O before the pump completely controlled his breathing. Refractory subjects were brought into step by starting at 18 to 20 cmH_2O and coming down quickly to 5 to 10 cmH_2O [12]. The tank kept a rhythm set by hand, while the ventilator of Section 4.5 starts a breath when the patient's own pull crosses its trigger.

4.6.4 A Leak at the Mask

Case 5 opens a 30 L/min leak at 20 s under a patient on pressure support who had triggered every breath at 454 to 455 mL. Without compensation three things break together. The leak's flow passes the trigger as each lockout ends, giving 11 auto-triggers in the 40 s to the end of the first minute, the first of them 2 ms after the leak opens, while only 3 of the patient's 10 efforts trigger anything. Every breath runs to the 2.50 s limit, because the flow never falls to a quarter of its peak. The measured volume reads 1521 to 1830 mL while the lung receives 103 to 414 mL and starts breaths from up to 5.99 cmH_2O of trapped pressure. With compensation the estimator learns 30.0 L/min, the auto-triggers stop after the first two, 9 of 10 efforts trigger, the breaths that follow last 0.68 to 0.77 s, and after one breath of 370 mL from the trapped volume the lung receives 454 to 462 mL, as it did before the leak.

> **TRY IT IN THE APP** **5 · A Leak**
>
> Load scenario 5 and press Run with Leak compensation off. After the leak opens at 20 s, the red rings on the pressure trace mark breaths the patient did not ask for, 11 of them before the end of the first minute. Press Reset, turn on Leak compensation on the expiratory valve card and run again: the auto-triggers stop after the first two.

4.6.5 Bronchospasm

Case 6 runs volume control at 24 min^{-1} with 1 s in and 1.5 s out while the resistance doubles to 20 $cmH_2O \cdot s/L$ from 20 s. The auto-PEEP rises from at most 0.48 to 2.58 cmH_2O, the per-breath fit reads 2.57 to 2.60 cmH_2O, and an expiratory hold requested at 90 s reads a total PEEP of 7.48 cmH_2O, an auto-PEEP of 2.48 against a true 2.49, while the airway pressure at the end of each expiration still reads the set PEEP. Only the expiratory time helps. With one setting changed at a time, the case reloaded before each, as its briefing directs, the auto-PEEP is 0.96 cmH_2O at 18 min^{-1} and 0.35 cmH_2O at 14 min^{-1}, and a 0.7 s inspiration, which leaves 1.80 s out, gives 1.79 to 1.80 cmH_2O. A PEEP of 10 cmH_2O leaves the trapping at 2.58 cmH_2O and lifts the plateau from 16.0 to 21.0 cmH_2O.

4.6.6 Identification Breath by Breath

Case 7 fits every breath of volume control while the lung stiffens to 30 mL/cmH_2O at 40 s, the resistance doubles from 80 s and the patient starts 5 cmH_2O efforts at 160 s. On the passive lung each fit recovers R within 0.5 %, C within 0.2 % and the auto-PEEP within 0.04 cmH_2O at both compliances, except the breath during which the lung stiffens, whose resistance comes out 42 % low, and while the resistance ramps the fit runs 0.5 to 1.0 % high, since R changes within the breath. The inspiratory hold at 20 s reads 13.44 cmH_2O, exactly the true plateau, which gives a static compliance of 49.8 mL/cmH_2O, and the expiratory hold reads 5.03 cmH_2O, an auto-PEEP of 0.03 cmH_2O. Once the patient breathes, every breath the patient triggers fits the resistance 21.6 to 21.8 % low and the compliance 10.8 to 12.0 % high, and by 220 s the smoothed resistance has drifted to 15.65 $cmH_2O \cdot s/L$ against 20.00. Learning only from machine-triggered breaths holds it at 17.80, since an effort can begin inside a breath the machine started.

4.6.7 Three Kinds of Asynchrony

Case 8 runs 120 s in three parts against a weak patient of 3 cmH_2O at 20 min^{-1}. With the flow trigger at 15 L/min, 8 of 14 efforts are missed and the patient gets backup breaths at 8 min^{-1}. At 40 s the trigger is softened to 0.5 L/min as a 2 L/min leak opens, and 13 of the 14 breaths that follow are auto-triggers. At 80 s the cuff is sealed, the mode becomes volume control with a 0.6 s inspiration and the patient pulls 12 cmH_2O for 1.5 s, and 13 of 14 efforts trigger twice. The second breath stacks on the first, so the plateau reaches 23.7 cmH_2O where the first breath of each pair stays at 14.4 to 14.8 cmH_2O, from up to 10.31 cmH_2O of trapped pressure. A 2 L/min trigger set before Run catches all 14 efforts of the first part, and set back to 2 L/min after the scripted change at 40 s it catches all 13 of the second without firing once on the 2 L/min leak.

4.6.8 A Leak No Blower Can Hold

Case 9 runs pressure control at 10 cmH_2O above a PEEP of 8 cmH_2O with compensation on, and at 20 s the mask comes away, 300 L/min at 10 cmH_2O. The estimator measures the leak as 300 L/min, the inspiratory valve is fully open from 21.8 s on, and the airway pressure sits at 3.45 to 3.46 cmH_2O in inspiration and expiration alike, the balance of Section 4.4, so no breath reaches the lung. The ventilator raises PEEP NOT HELD, LEAK and LOW TIDAL VOLUME, the status strip shows the first, and the CO_2 climbs from 40.0 to 42.9 mmHg between 20 and 60 s. No controller makes the blower bigger, and the alarm and a person at the mask are the answer.

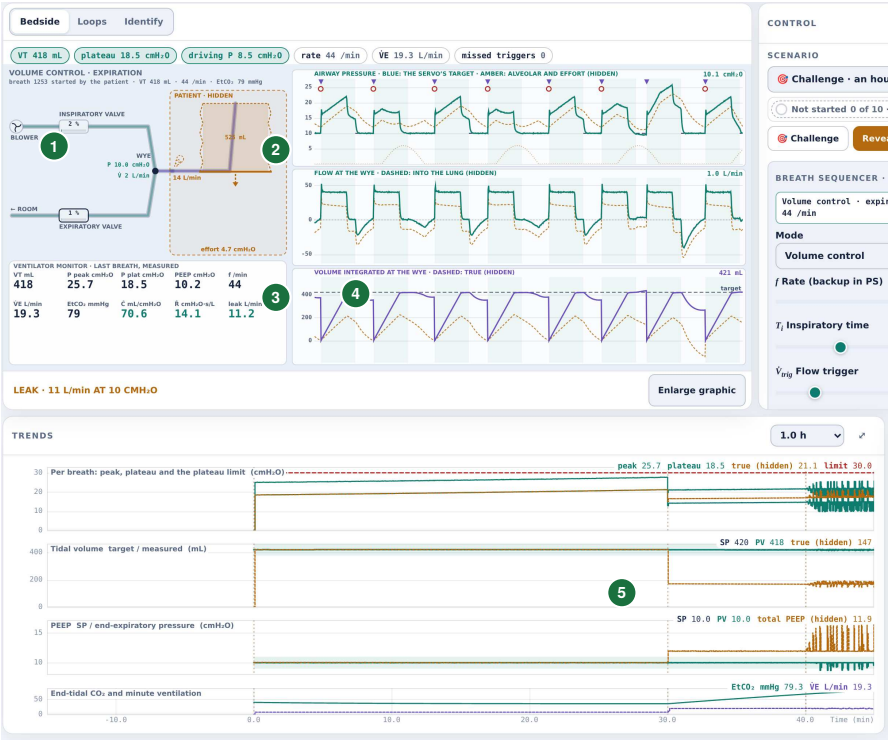


Figure 4.3 The challenge as shipped, volume control at 420 mL, 18 min^{-1} and a PEEP of 10 cmH_2O, at minute 45, Bedside view with a one-hour trend window, cropped to the plant view and the trends: (1) the circuit with its two valves and the wye, (2) the hidden patient, (3) the ventilator monitor, (4) the waveforms and (5) the tidal volume trend. The clock in the header and the scorecard of the Learn panel are cut. The header of the plant view reads volume control, expiration, breath 1253 started by the patient, and the monitor reads a tidal volume of 418 mL, a peak of 25.7 cmH_2O, a plateau of 18.5 cmH_2O, PEEP 10.2 cmH_2O, 44 min^{-1}, 19.3 L/min of minute ventilation, an end-tidal CO_2 of 79 mmHg, $\hat{C}$ 70.6 mL/cmH_2O, $\hat{R}$ 14.1 $cmH_2O \cdot s/L$ and a leak of 11.2 L/min, while the hidden panel shows the true 14 L/min leak and an effort of 4.7 cmH_2O. In the 10 s of waveforms all eight breaths are marked as patient-triggered, seven carry the red ring of an auto-trigger, and the volume integrated at the wye reaches the 420 mL target each time while the dashed true volume peaks at 200 to 225 mL and falls back as the leak drains the lung in each pause. The status strip reads LEAK, 11 L/min at 10 cmH_2O. Over the hour the trends show the true tidal volume leaving 420 mL at minute 30 and ending the window at 147 mL, the true plateau at 21.1 cmH_2O against a measured 18.5, the total PEEP at 11.9 cmH_2O against a measured 10.0, and the CO_2 at 79.3 mmHg.

4.6.9 An Hour on the Ventilator

The challenge ventilates for an hour while the lung stiffens steadily from 50 to 25 mL/cmH_2O, a 14 L/min leak opens past the cuff at minute 30, and from minute 40 the patient breathes at 22 min^{-1}, each effort growing to 6 cmH_2O over a minute. The target, scored on the hidden record, asks for at least 98 % of breaths within 10 % of 420 mL, no plateau above 30 cmH_2O, no auto-PEEP above 3 cmH_2O, and at most 10 missed efforts and false triggers together, and it allows 2 % of breaths out of band because the first few breaths of a new leak come before it is learned. Stiffening alone cannot fail volume control here, since at a PEEP of 10 cmH_2O and 420 mL the plateau reaches 30 cmH_2O only below 21 mL/cmH_2O and the lung stops at 25, so the hour turns on the leak. The shipped configuration, volume control at 18 min^{-1}, is faultless for half an hour, with 420 to 422 mL per breath and a plateau that rises to 21.2 cmH_2O. The leak then auto-triggers it 1211 times, at 47.7 min^{-1}

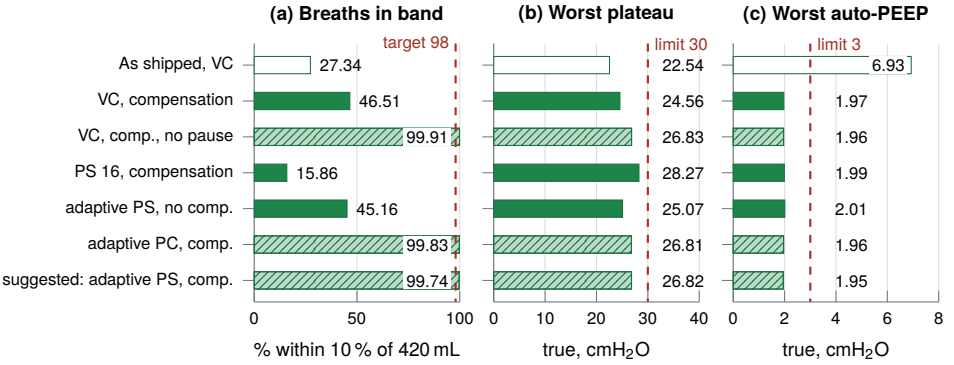


Figure 4.4 The seven configurations of Table 4.6 over the hour of the challenge: (a) the share of breaths within 10 % of 420 mL against the 98 % target, (b) the worst true plateau against 30 cmH_2O and (c) the worst true auto-PEEP against 3 cmH_2O, limits dashed. White: the shipped configuration. Solid: the other rows that fail. Hatched: the rows that pass. Every configuration keeps the plateau under its limit, every one but the shipped one keeps the auto-PEEP under its limit, and every row that fails falls short of the share of breaths in band.

between minutes 30 and 40, and each breath sends part of its volume out of the leak, so the lung receives 139 to 193 mL and starts breaths from up to 6.93 cmH_2O. Only 27.34 % of the hour's breaths are in band, and the CO_2 ends at 111.0 mmHg, as shown at minute 45 in Figure 4.3.

Table 4.6 compares the configurations, and Figure 4.4 draws three of its columns as bars. Adaptive pressure support with leak compensation, the configuration the challenge suggests, meets the whole target, the same whether it is revealed before Run or carried through a Reset, with 99.74 % in band, 1.74 points above the 98 % required, a plateau of at most 26.82 cmH_2O, auto-PEEP of at most 1.95 cmH_2O, one missed effort and two auto-triggers, and it ends with 14.2 cmH_2O of support and a CO_2 of 29.3 mmHg, on which the target is silent. Its three misses, 517 mL, 371 mL and 516 mL, are the two breaths before the new leak is learned and the first after it, all within 5.4 s of the leak opening. On seeds 1 to 5, 7 and 99 it passes with 99.65 to 99.74 % in band and auto-PEEP of 1.92 to 1.96 cmH_2O, and the shipped configuration fails on all of them with 27.25 to 27.30 %. Volume control with compensation alone reaches 46.51 %, because the lung drains through the leak during the 0.2 s pause with both valves shut, and without the pause it passes. Adaptive support without compensation still takes 660 auto-triggers, and a fixed support of 16 cmH_2O with compensation leaves 84 % of breaths out of band as the compliance halves. The target is a worst case over breaths. With the leak slider set to another size when the leak opens, an exploration the challenge itself does not credit, the shipped volume control passes with no leak or 1 L/min, fails at 2 L/min on 611 auto-triggers with 99.16 % still in band, and collapses to 39.07 % at 3 L/min. The suggested configuration passes at 20 L/min and fails at 30 L/min on a single breath, the second after the leak opens, which starts 4.58 cmH_2O above PEEP, while from minute 31 no breath exceeds 0.21 cmH_2O.

Table 4.6 The Challenge Over 60 min at the Default Seed. The Volume Is the Share of Breaths Within 10 % of 420 mL, and Triggers Are Missed Efforts and False Triggers Together

Configuration	Vol. (%)	P_{plat}	PEEP$_i$	Trig.	Pass
as shipped, VC	27.34	22.54	6.93	1211	no
VC, compensation	46.51	24.56	1.97	4	no
VC, compensation, no pause	99.91	26.83	1.96	4	yes
PS 16 cmH_2O, compensation	15.86	28.27	1.99	3	no
adaptive PS, no compensation	45.16	25.07	2.01	660	no
adaptive PC, compensation	99.83	26.81	1.96	3	yes
suggested, adaptive PS, comp.	99.74	26.82	1.95	3	yes

Plateau and auto-PEEP are the worst true values, in cmH_2O.

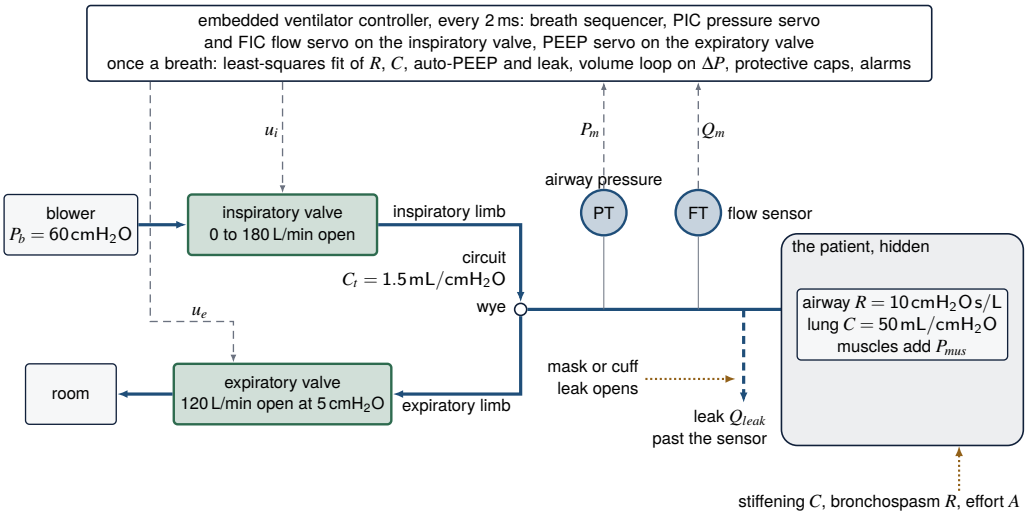


Figure 4.5 The loops of Section 4.5 with the hardware of an intensive care ventilator. The blower at P_b feeds the inspiratory valve, the final element of the pressure servo (PIC) and the flow servo (FIC). The expiratory valve vents the circuit to the room and holds PEEP. The only sensors are the airway pressure transmitter (PT) and the flow sensor (FT) at the wye, read by the embedded controller every 2 ms. Everything in the shaded box, and the leak between the sensor and the patient, is hidden from it. Thick solid arrows carry gas, thin dashed arrows signals, dotted arrows disturbances. Ranges are those of Table 4.2.

> ✦ **DID YOU KNOW? A Fifth of a Second Decides the Hour**
>
> From the simulator: with leak compensation on, volume control keeps 46.51 % of the challenge's breaths within 10 % of the target. The same configuration without its end-inspiratory pause keeps 99.91 %, the highest share of any configuration in Table 4.6.

4.7 Technology in Practice

The blower, the two valves and the two transmitters of Figure 4.1 stand for the hardware of an intensive care ventilator. Figure 4.5 draws the loops of Section 4.5 with that hardware in place of the schematic's symbols.

What Measures It

Airway pressure is read by a pressure transducer and flow by a flow sensor, which in ventilators is most often a differential pressure sensor, a hot-wire anemometer or an ultrasonic meter. Where the flow sensor sits matters. A sensor near the expiratory valve also counts the gas compressed in the circuit, which grows with the peak pressure and changes as water condenses, while a sensor at the wye does not [19]. The chapter's sensors sit at the wye, read the circuit pressure P and the flow $\dot{V} + Q_{leak}$ of Equation (4.3), and carry Gaussian noise of 0.05 cmH_2O and 0.3 L/min with no drift.

> **TECHNOLOGY** **Sensor: The Flow Sensor at the Wye**
>
> United States regulation describes a pneumotachometer as a device that finds gas flow from the pressure drop across a known resistance, a set of capillaries or a metal screen [20]. Ventilators most often use differential pressure sensors, hot-wire anemometers or ultrasonic meters. In a variable-orifice sensor a slit flap opens wider as the flow rises, and a jet from a narrow fitting can set the flap fluttering. A heated wire is cooled by the passing gas, reads most finely at low flow and can drift at zero as the gas temperature changes. The standard for critical care ventilators allows a measured volume above 50 mL to be off by 4.0 mL plus 15 % [19]. Water condensing in the circuit can show as a rhythmic ripple on the expiratory flow trace and trigger breaths the patient did not start [21].

What Moves It

The final elements are the inspiratory valve, which meters gas from the supply into the circuit, and the expiratory valve, which lets it out and holds PEEP. In the chapter each is an orifice whose opening follows its command through a lag of 5 ms, with the inspiratory valve passing 180 L/min fully open into an open airway. Only the inspiratory valve can add gas, which is the one-sided authority that sets the largest leak of Section 4.4.

> **TECHNOLOGY** **Final Element: Inspiratory and Expiratory Valves**
>
> A continuous ventilator, a Class II device in United States regulation, mechanically controls or assists the patient's breathing [22]. A system of solenoid-driven valves has been the design of choice for modern ventilators, which must deliver precise volumes, rates and PEEP and allow rapid adjustment. One open low-cost design switches the inspiratory gas with a solenoid valve and holds PEEP with a pneumatically driven exhalation valve near the patient. Such valves fail safe to a defined open or closed position, last many cycles and act fast. The standard for critical care ventilators asks for an anti-asphyxia valve, a mechanical relief valve against overpressure, and alarms for low pressure, which means a disconnected circuit, for high pressure and for insufficient flow [23].

Where the Controller Runs

Open designs show where such loops run: one emergency ventilator's monitor sampled its pressure sensor 100 times a second on a microcontroller [24], and a low-cost solenoid-valve ventilator was controlled through a microcontroller board [23]. A modern intensive care ventilator answers a patient's trigger in under 100 ms [21]. The chapter's controller runs every 2 ms behind a 10 ms trigger filter, and the fit and the volume loop run once a breath, a layer above the servos. The essential performance of the whole machine is set by the standard for critical care ventilators [10].

What Is Modernizing It

Three developments bear on these loops. Ventilation can now be coupled to the electrical activity of the diaphragm, measured by an esophageal catheter, so that the support follows the patient's neural output. Synchrony improved, though the clinical impact still had to be determined. Transpulmonary pressure, the airway pressure less a measured esophageal pressure, and electrical impedance tomography are being studied for setting PEEP [25]. Both would give the controller a view of the effort and the lung that the wye of this chapter cannot. Home ventilators, finally, send data through the internet to

cloud systems, where clinicians review usage, estimated unintentional leak, tidal volume and minute ventilation [4].

> **IN PRACTICE** **Reading the Waveforms at the Bedside**
>
> A basic anesthetic monitoring standard requires that, whenever a mechanical ventilator controls the breathing during anesthesia, a device in continuous use detects a disconnected breathing system and sounds an audible alarm [26]. Beyond the alarms, the clinician reads the pressure and flow waveforms. A total rate above the set rate in a controlled mode suggests auto-triggering, whose causes include air leaks, the trigger setting and condensation in the circuit. A modern ventilator answers a trigger in under 100 ms when its sensitivity is set correctly. Visual inspection is the accepted method, yet in one study intensive care physicians recognized fewer than a third of the asynchronies [21].

4.8 Limitations

The application teaches the control structure of a ventilator and is not a medical device. Its lung, its patient and every limit it draws were chosen to make the control lessons visible, nothing in it has been validated against patient data, and none of its settings or results may be carried to a ventilator that serves a person. The lung-protective targets are those of a trial [2], the requirements a real ventilator meets are those of its standard [10], and the asynchrony classes come from the clinical literature [9].

> **OPEN CHALLENGE** **A Closed Loop With a Patient Inside**
>
> A physiological closed loop feeds a measurement of the patient back to the ventilator's settings, and an international collateral standard now covers such controllers. Their sensors limit them. Intravascular sensors of arterial carbon dioxide were too slow for some loops and are no longer sold, so control fell back on end-tidal carbon dioxide, whose gap to the arterial value grows in a diseased lung. Sensor failure, unpredictable disturbances and software errors remain open problems [25]. The volume loop of Section 4.5 meets a mild form of this when it freezes while a new leak is learned. Progress would be safety concepts that keep an automated loop harmless, transparent and lighter on the clinician's workload [25].

The modeling limits are those of the assumptions in Section 4.3.5. One linear compartment cannot recruit, derecruit or overdistend, so the application cannot show why PEEP is set in ARDS or why a pressure-volume curve bends. The scripted effort ignores CO_2 and support, so the patient never fights back or tires. The machine's laws are known exactly to its controller, its sensors do not drift, its leak has a fixed law, oxygenation is absent, and the audit uses an effort that a bedside cannot see. Every computer replays the same hour from the same seed, which no patient does.

> **OPEN CHALLENGE** **Seeing the Effort the Wye Cannot**
>
> A review of 19 studies of automatic asynchrony detection by rules, machine learning and deep learning reported an average sensitivity of 0.80 and specificity of 0.93. Yet most detectors were available only offline, found a small subset of asynchronies, mostly ineffective efforts and double triggers, or were still in development or validation, as 16 of the 19 were. Only 11 studies had a reference measurement of the patient's effort, such as esophageal pressure or the electrical activity of the diaphragm [27]. The truth audit of Section 4.3.5 uses that reference, the hidden P_{mus}. Progress would be detectors of several kinds of asynchrony, validated on new data against a measured effort and run in real time at the bedside [27].

4.9 Conclusion

A ventilator holds what its two sensors at the wye report, and this simulator measures how far that can be from the breath the lung receives. On a lung stiffened to 18 mL/cmH_2O, volume control keeps 420 mL by letting the plateau reach 31.3 to 31.5 cmH_2O, pressure control keeps its plateau by letting the volume fall to 179 mL, and the protective layer, working from the identified compliance, holds both at 393 to 396 mL under 30 cmH_2O. Trapped pressure follows the expiratory time alone, 5 to 8 %

above its closed form. A leak past the wye shows up as auto-triggers, hung breaths and a measured volume of 1521 to 1830 mL for 103 to 414 mL delivered, and a 300 L/min leak holds the airway at 3.46 cmH_2O whatever the controller does. The per-breath fit identifies a passive lung within 0.5 %, and an effort that triggers biases it systematically. Over the hour, volume control with a leak keeps 27.34 % of its breaths in band and adaptive pressure support with compensation 99.74 %. The lung is one linear compartment and the patient a script, and a fuller model would add recruitment, a chemoreflex, oxygenation and a changing mask leak. In this browser plant the measured and the delivered breath can be compared on every cycle.

KEY POINTS

- A ventilator holds what its two sensors at the wye report, and that can be far from the breath the lung receives.
- On a lung stiffened to 18 mL/cmH_2O, volume control keeps 420 mL by letting the plateau reach 31.3 to 31.5 cmH_2O, and pressure control keeps its plateau by letting the volume fall to 179 mL.
- A leak past the wye shows up as auto-triggers, hung breaths and a measured volume of 1521 to 1830 mL for 103 to 414 mL delivered.
- The per-breath fit identifies a passive lung within 0.5 %, and an effort that triggers biases it systematically.

Where else this applies. Cycles whose events the plant partly decides return in Volume 8, Chapter 7 and Chapter 2.

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4.10 Exercises

4.1 ⌕ Concept check · 1 min

In case 2 the ventilator delivers 420 mL in volume control at a PEEP of 8 cmH_2O, and at 30 s the lung stiffens from 50 to 18 mL/cmH_2O. What happens with the protective layer off?

(a) The volume falls to about 179 mL and the plateau stays near 18 cmH_2O

(b) The volume stays near 420 mL and the plateau climbs past the 30 cmH_2O limit

(c) The flow servo saturates, so the volume and the plateau both fall

(d) The volume falls and the plateau climbs, since the servo splits the error

4.2 ⌕ Concept check · 2 min

In case 6, after the bronchospasm, the lung has $R = 20\,cmH_2O\,s/L$ and $C = 50\,mL/cmH_2O$, and each expiration lasts 1.50 s. Which single change of setting lowers the true auto-PEEP?

(a) Raising PEEP from 5 to 10 cmH_2O, which holds the airways open in expiration

(b) Turning on the protective layer, which caps the plateau at 30 cmH_2O

(c) Lowering the rate, which gives each expiration more time constants to empty

(d) Raising the tidal volume, so that each breath clears the lung more fully

4.3 Concept check · 2 min

In case 7, from 160 s, a patient with 5 cmH_2O efforts triggers the volume-controlled breaths. How does the per-breath least-squares fit err on the breaths the patient triggers?

(a) It scatters at random about the truth, so the smoothed estimate stays unbiased

(b) It reads the resistance high and the compliance low, as a narrowed airway would

(c) It does not err, because each effort ends before the flow of the breath begins

(d) It reads the resistance low and the compliance high, by about the same amount on every breath

4.4 Theory and calculation · 6 min

Use Equation (4.5) for a passive lung with $R = 10\,cmH_2O\,s/L$.

(a) Volume control delivers 420 mL at a PEEP of 8 cmH_2O. Find the plateau at $C = 50$ and at $C = 18\,mL/cmH_2O$. *Checkpoint:* 16.40 cmH_2O and 31.33 cmH_2O.

(b) Pressure control holds 10 cmH_2O above PEEP for $T_i = 1.0$ s with a rise time $T_r = 0.1$ s. Find the tidal volume at the same two compliances. *Checkpoint:* 425.2 mL and 179.1 mL.

(c) The challenge runs volume control at 420 mL and a PEEP of 10 cmH_2O. Find the compliance below which the plateau exceeds 30 cmH_2O, and say whether the stiffening to 25 mL/cmH_2O alone can fail the plateau target. *Checkpoint:* 21 mL/cmH_2O, so it cannot.

4.5 Theory and calculation · 5 min

Case 6 after the spasm has $R = 20\,cmH_2O\,s/L$, $C = 50\,mL/cmH_2O$, volume control at $V_T = 420$ mL and $T_i = 1.0$ s with no pause.

(a) Find RC, the expiratory time at 24 min^{-1} and the trapped pressure from Equation (4.6). *Checkpoint:* 1.00 s, 1.50 s and 2.41 cmH_2O.

(b) Repeat the trapped pressure at 18 min^{-1}. *Checkpoint:* 0.90 cmH_2O.

(c) The engine measures 2.58 and 0.96 cmH_2O. Find by how much it exceeds the closed form in each case, and give the reason. *Checkpoint:* About 7 and 6 %.

4.6 Theory and calculation · 7 min

The orifice law of Equation (4.3) is $\psi(\Delta p) = \Delta p/\sqrt{|\Delta p| + 0.1}$ with pressures in cmH_2O. The blower holds 60 cmH_2O, the fully open inspiratory valve passes 180 L/min into an open airway, and a leak is entered as its flow at 10 cmH_2O.

(a) Find the flow of the fully open inspiratory valve into a circuit held at 8 cmH_2O. *Checkpoint:* 168 L/min.

(b) Find the flow that a leak entered as 300 L/min takes at 8 cmH_2O. *Checkpoint:* 268 L/min.

(c) Find the largest leak, entered at 10 cmH_2O, against which a PEEP of 8 cmH_2O can still be held, and say what leak compensation adds above it. *Checkpoint:* 187.6 L/min. Nothing.

4.7 App challenge · 8 min

Load scenario 2, Volume control and a stiffening lung. Use the default seed and the speed 5×, and run each case to 120 s.

(a) Run the scenario as shipped, with the Lung-protective layer off. Read the true plateau over the last 10 s in the exported CSV column `pplat_true_cmH2O`, and the tile Highest plateau (true). *Checkpoint:* 31.3 cmH_2O, within 0.1 cmH_2O. Tile 31.5 cmH_2O.

(b) Turn on the Lung-protective layer, press Reset and run again. Read `vt_true_mL` and `pplat_true_cmH2O` over the last 10 s, and the same tile. *Checkpoint:* 395 to 396 mL at 29.9 to 30.0 cmH_2O. Tile 31.5 cmH_2O.

Explain why the tile reads the same in both runs.

4.8 App challenge · 7 min

Load scenario 6, Bronchospasm and auto-PEEP. Use the default seed and the speed 5×, run each case to 120 s and read the tiles Highest auto-PEEP (true) and Highest plateau (true). Reload the case with the reload button before each change, and make the change before Run.

(a) Run the scenario as shipped, at 24 min^{-1}. *Checkpoint:* 2.58 cmH_2O and 16.0 cmH_2O.

(b) Set Rate to 18, then to 14 min^{-1}. *Checkpoint:* 0.96 and 0.35 cmH_2O.

(c) Leave the rate at 24 and set PEEP to 10 cmH_2O. *Checkpoint:* 2.58 cmH_2O and 21.0 cmH_2O.

Accept the auto-PEEP within 0.02 cmH_2O, and compare the results with the closed form.

4.9 App challenge · 8 min

Load the challenge, an hour on the ventilator. Use the default seed and the speed 60×, and run the full hour each time. Read the tiles Breaths within ±10 %, Highest auto-PEEP (true), the Audit and End-tidal CO_2.

(a) Run the challenge as shipped, in volume control. *Checkpoint:* 540 of 1975, 27.3 %. 6.93 cmH_2O. Audit 0, 1211, 0. 111.0 mmHg.

(b) Reload, and before Run set Mode to pressure support, Leak compensation on and Adaptive support on. Run the hour again. *Checkpoint:* 1157 of 1160, 99.7 %. 1.95 cmH_2O. Audit 1, 2, 0. 29.3 mmHg.

Say which part of the target the first run fails, and what each of the two switches in the second run contributes.

4.10 Application area · 4 min

The app's lung-protective values come from the ARDS Network trial. Take a predicted body weight of 70 kg.

(a) Find the tidal volume at 6 mL/kg and the volume cap at 8 mL/kg. *Checkpoint:* 420 mL and 560 mL.

(b) The trial reported a mortality of 31.0 % against 39.8 %. Find the absolute difference and the number of patients treated for each death avoided. *Checkpoint:* 8.8 points, about 11 patients.

(c) In case 2 after the stiffening, the plateau is 31.3 at a PEEP of 8 cmH_2O. Find the driving pressure, and compare it with the 15 cmH_2O line the app draws. *Checkpoint:* 23.3 cmH_2O, 8.3 cmH_2O above the line.

4.11 Application area · 4 min

The carbon dioxide of the app is one store with a production of 200 mL/min, a capacity of 45 mL/mmHg, a dead space of 150 mL and $K = 0.863$ in Equation (4.4).

(a) Find the alveolar ventilation and the steady CO_2 for 420 mL at 16 min^{-1}. *Checkpoint:* 4.32 L/min and 39.95 mmHg.

(b) Find how fast the CO_2 rises in apnea. *Checkpoint:* 4.44 mmHg a minute.

(c) In the challenge as shipped the CO_2 reaches 111.0 mmHg. Name two responses a real patient would show that the app's patient cannot.

4.12 Review the agent · 5 min

An AI assistant is shown the challenge at minute 45, run as shipped, and writes: "The monitor reads a tidal volume of 418 mL against the 420 mL target and a plateau of 18.5 cmH_2O, far below 30. The identified compliance is 70.6 mL/cmH_2O, up from 50 at the start, so the lung is improving. The leak

reads only 11.2 L/min. Keep volume control, and consider lowering PEEP as the lung recovers.” Find the flaw and say how to check it.