Zen and the Art of Nomenclature Maintenance: A Revised Approach to Respiratory Symbols and Terminology

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In this paper we point out that there are different entities involved in the mathematical descriptions, or models, of the respiratory system: *variables* and *parameters.* These, in turn, can be divided into different types. Variables can be *primary variables, difference variables,* or *change variables*. *Difference variables* express the difference between primary variables measured simultaneously at 2 locations. *Change variables* are primary variables measured relative to fixed reference values. Parameters that appear in input-output models that are valid over a wide range of inputs can be interpreted as *properties*. There are 3 levels of properties, depending on the detail included in the model. If the model specifically includes the geometry of the system and the substances of which the system is composed, then the parameters in the model are *material properties*. If the model includes the general structures that compose the system, the parameters are *structural properties*. And if the model describes the behavior of the system as a whole with no detail included pertaining to internal makeup, then the parameters can be considered *system properties*. Parameters that appear in mathematical descriptions of input and/or output wave shapes can be interpreted as *waveform characteristics*. *General waveform characteristics* are attributes of arbitrary inputs and/or outputs. However, in those special cases in which a system is subjected to a well-defined, specialized input and the output waveform is described mathematically (even if only at a single point), the parameter(s) in such descriptions can be considered *system response characteristic(s)*. We suggest that the symbols and names given to these various entities should follow well-defined guidelines that distinguish among the entity types. These guidelines should include symbol and name conventions and also sign conventions and expected unit ranges on appropriate measurement scales. One such set of conventions would be as follows. Italicize all *variables.* Use upper-case for *primary* (absolute) variables. Use the delta symbol (Δ) to denote *difference* variables (difference between 2 locations). Use lower-case letters for *change* variables (change relative to a reference, or operating, point) and for abbreviations (eg, "pl" for "pleural"). Use upper-case characters to represent the initial letters of words (eg, "AO" for "airway opening"). Make bold nonitalicized groups of letters used for *properties* (upper-case, lower-case, multi-height). Do not bold or italicize groups of letters used for characteristics (upper-case, lower-case, multi-height). Compound symbols are those that include subscripts and/or superscripts. Subscripts following a symbol indicate location, direction, or index (time); if more than one subscript, separate them by commas. Superscripts following a symbol indicate a component, or it can indicate a power if the symbol is enclosed in parentheses. Letters on the same line as initial letter but in smaller type are part of the generic symbol. Arguments are enclosed in parentheses; parentheses are also used to isolate compound symbols from powers or additional subscripts. Adapt currently standard symbols to retain their identity but conform to the

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above conventions. The sign of an entity is always dictated by and its interpretation is based on the model in which the entity is used. Units used are consistent with measurement resolution and accuracy. Copious examples of the applications of this set of suggested conventions are given in the text and in 4 tables. Our hope is that the presentation of these suggestions will start a dialogue in the field and will influence journal and book publishers to adopt a consistent set of conventions for the names and symbols used for respiratory-system-related terms. *Key words: respiratory mechanics/physiology, terminology, transrespiratory pressure, transairway pressure, transpulmonary pressure, transalveolar pressure, transthoracic pressure, transchestwall pressure, transdiaphramatic pressure, transabdominalwall pressure, models, systems, definitions, respiratory system model.* [Respir Care 2006; 51(12):1458–1470. © 2006 Daedalus Enterprises]

Introduction

In the early 1970s a colleague and I (FP) were invited to a biomechanics conference. We decided to drive there in a van and thus could provide transportation for several mechanical engineering graduate students who wanted to attend. During the 4 or so hours' drive, various conversations took place, one of which was very enlightening.

After learning that I was studying the mechanics of the respiratory system, one of the students made the comment, "I looked into doing a project in pulmonary mechanics but decided not to after a preliminary literature review. It is just too confusing. The terminology is difficult to understand and, even though the authors' bread and butter are pressure and volume, most don't seem to appreciate what a pressure is and are inconsistent when relating it to other variables."

Another student said, "I know what you mean. But you have to realize that in the respiratory literature even though they use the symbol *P*, they're not necessarily talking about 'pressure'; they're usually talking about 'pressure difference.' And the 'volumes' they refer to are often really 'changes in volume.' It's just that the same symbols keep popping up but can stand for different things."

"I figured that out after awhile," said the first student, "but I just got tired of translating and trying to decide what they meant to say every time I started reading a different paper."

The remainder of the trip gave me time to reflect on these comments. I realized that I had been imbedded in respiratory topics for so long that I had developed internal mental transformations that allowed me to read and automatically interpret the mathematical and verbal descriptions in the physiology and clinical literature so that they usually made physical sense to me. I had lost sight of the difficulties that a respiratory mechanics novice, including one trained in the physical sciences or engineering, would have during his or her introduction to the field.

It's now more than 3 decades later, and even though we've attempted to point out the problems that exist,[1,2] several tries at nomenclature reform[3–6] have done little to help the situation.[7,8] There are several reasons for this.

One is the large "installed base" of practicing physicians and physiologists who were trained in simplistic ways of thinking and talking about respiratory mechanics. These become the teachers of the next generation. Many of these teachers don't appreciate the inaccuracies they propagate in their classrooms and in the papers and textbooks they write. But they are not entirely to blame, because most graduate life science and clinical students are not required to have the background needed to understand the subtleties and nuances of critical concepts. Added to this is the requirement imposed upon clinicians to provide simple, straightforward explanations of disease processes and treatments to patients and their caregivers. Realizing this, many medical students do not see the need, and even protest attempts to teach them anything more abstract than the conventional wisdom. Consequently, and unfortunately, it appears that, in many cases, the level of understanding possessed by clinicians may not be much higher than the level of the explanations the clinicians give to their patients. Yet these same medical students, after they acquire a degree, can get the idea that they are qualified to do research, and proceed to submit papers filled with ad hoc terminology and imprecise theories. Of course, those critiquing these papers before publication are peers of these authors and may have comparable backgrounds, so many such papers get into the literature. Consequently, simplified explanations are propagated and, for want of a better term, "novel" mathematics is used to express complicated concepts.

In actuality, a dichotomy has developed between classical respiratory physiology and engineering-based analyses of respiratory function. Whereas the former uses its entrenched terminology, the latter typically finds this terminology inadequate and devises hybrid terminology and symbols that may be useful for the paper at hand but lack generality applicable in a wider context.[8]

So where do we stand now and how can we change it? To explore such questions let us review a little bit of the philosophical underpinnings of respiratory physiology.

Zen

As human beings, we think, learn, and explain in terms of analogies, similes, and metaphors.[9] That is, we describe complicated concepts and objects in terms of simpler, better-understood concepts and objects. We might say the rib cage is a pump, not because it is made of steel and is powered by electricity, but because it moves air as a pump does, and supposedly we all know what a pump does.

The basis of all metaphors is the concept of a system. A system comprises a relationship among a set of objects. A different relationship among the objects is a different system. For example, the parts of a piston pump and a compressed air motor can be exactly the same. However, in the pump, the piston is driven by an external force to compress the air in its cylinder, whereas compressed air is introduced into the cylinder of the motor to produce an external force. Therefore, in this sense, a pump and a motor are different systems, even though their physical components are exactly the same.

On the other hand, 2 systems can be considered similar or equivalent even though their physical (or conceptual) components are completely different if the relationship among those components is equivalent. Thus, a wood and cloth bellows has no parts in common with the supercharger on your Porsche, but in the sense that they each compress air and deliver it through a nozzle, the bellows and the supercharger are similar or equivalent systems. One can be used to describe the other.

Models

We refer to systems that are, in some sense, similar or equivalent, as models of each other. All that is required of a system to be a model of another system is a relationship among its objects that is equivalent in some sense to the relationship of the other system. Therefore, models can have any form.

We can have 2 physical systems that are models of each other, such as a bellows and a supercharger. Likewise, we can have a verbal expression that implies the same relationship among parts as the relationship among the parts of a physical system. Thus, we can associate the metaphor "pump" with a physical system such as the rib cage, and it is no less of a model of that physical system than is, say, a physical bellows.

Since a metaphor draws a verbal equivalence between 2 systems, metaphors are *verbal models*. In contrast to *physical models*, verbal models are classified as *abstract models*. Verbal models are limited by their very nature to qualitative descriptions of system behavior. Other members of the class of abstract models are *mathematical models*. These usually represent higher levels of abstraction than verbal models and can produce quantitative descriptions. The component objects in mathematical models are variables, and the relationships among the variables are mathematical expressions. For example, instead of invoking the metaphor of a supercharger for a bellows, we could just as effectively describe the bellows by the mathematical relationship among the change in its internal volume as its handles are pushed together, the increase in its internal pressure, and the flow of gas it produces.

Typically, one set of variables is considered the forcing, or input, variable(s), and a second set is considered the response, or output, variable(s). Thus, mathematical descriptions of physical processes are often referred to as *input-output models*.

The form of the mathematical expression we use for a model will depend on 2 considerations: the use to which the model will be put, and the observations (measurements) we can make of the system being modeled. For instance, in the case of the bellows we may want to calculate the profile of internal pressure change throughout the pump cycle, or we might just want to relate the volume delivered for particular displacements of the handles. These would require different mathematical expressions, both describing the same device.

We can see that there is no one unique model for any particular system. Taking this to the extreme, theoretically there could be an infinite number of models for any given system. In fact, realization of this is what caused Phaedrus, the protagonist in Robert Pirsig's novel, *Zen and the Art of Motorcycle Maintenance*,[10] to have an emotional breakdown, give up on his research, and begin his odyssey.

However, the problem lies not so much in the plethora of models available as in the way we can so easily forget that they are models in the first place. In fact, we can never make statements about a given system of interest; statements are always about an image or model of a system. Every time we describe a system (ie, describe our observations of a system), we use analogies or models. Thus, we speak in metaphors. Even the taking of measurements implies that the measured variables are related in some way, and that implied relation is the model. This may seem counter-intuitive but a little thought will show that it is obvious.

We can hypothesize many mathematical expressions as candidate models for a system. However, only the expression(s) that can be tested to show that it does (they do), in fact, represent the system in the manner and to the accuracy we desire would be considered valid models of the system for our intended purposes. This means we must perform controlled experiments and measure the appropriate variables under the variety of conditions for which we want the model to be valid. Only in this way can we demonstrate the equivalence of the model's behavior to that of the system being modeled.

So what does this have to do with the state of respiratory nomenclature? Well, we must realize that clinical practice operates in the world of verbal metaphors, and the physical and life sciences operate in the world of mathematical models. These worlds are necessary, albeit reluctant, bedfellows. And, as with all such situations, difficulties sometimes arise when the two must communicate, especially, as in this case, when they don't have a common language. Once this is acknowledged, we can develop a foundation for a coherent vocabulary that spans the disciplines. However, to do this we must address some specific details about systems in general and the respiratory system in particular.

Properties

The level of detail included in models can range from gross overall input-output relations to descriptions of the system subdivided into discrete segments to continuous models that include specifications of geometry and the materials that compose the system. Assuming that these descriptions are shown to be valid over a wide range of input conditions, the *parameters* (ie, constants) they contain can be interpreted as *properties* of the modeled system. The overall system models give rise to *system properties*, such as the real and imaginary frequency distributions of the impedance. Models that provide more detail about discrete elements making up the system define *structural properties* and are called *lumped-parameter models*. The parameters in the most detailed, continuous models are *material properties*. Thus, it is possible to develop mathematical models of physical systems at different levels of precision, limited by only 2 things: our ability to observe (make measurements on) the system (left brain activity) and our imagination (right brain activity).

Clinically useful mathematical models relate variables that can be measured using noninvasive or minimally invasive techniques at a limited number of locations on the patient, under conditions that the patient can tolerate, during maneuvers he or she is capable of performing. The resolution of the possible descriptions is limited to the subdivisions of the system between the measurement sites. Consequently, lumped-parameter models are generally most applicable to clinical practice.

Models that relate generalized forces, represented as pressures, to generalized displacements, represented as volume changes, describe the *mechanics* of a (pneumatic) system. Models that relate substance concentrations and/or partial pressures to mixture component (species) mass, gas, and/or liquid flows describe the *mass transport* of a system. Models that incorporate mechanics and/or gas transport models as subsystems, usually arranged in feedback loops, along with the logic and strategies required for the proper operation and interaction of these processes, describe the *control* aspects of the system.

The variables in these mathematical models represent measurable quantities and are most often expressed as functions of time. However, they can also be functions of frequency, as in the equations that define the (complex) impedance. They can also be functions of each other, as in the static "pressure-volume" curve.

The parameters in mechanics equations are interpreted as *mechanical properties* and as *gas or liquid* (eg, blood) *transport properties* in the mass transport models. Both mechanical and gas transport properties can be incorporated into control schemes for the system.

An example of a mathematical model often used to describe the mechanics of the pulmonary system is conventionally written:

$$P = \frac{V}{\mathbf{C}} + \mathbf{R}\dot{V} \tag{1}$$

where P, V, and $\dot{V}$, representing pressure, volume, and flow, respectively, are the variables of the equation (ie, variable functions of time). **C** and **R** are constants (ie, the parameters of the equation) considered to be the mechanical structural properties of the system (ie, compliance and resistance, respectively).

Equation 1 is referred to as a *linear model* because the relationship among its variables has the *form* of a linear equation (ie, $y = \mathbf{A}x + \mathbf{B}z$). Over limited ranges of their variables (eg, for the lungs, over a quiet breath), linear models can provide very useful approximations to the more complicated, nonlinear relationships physical systems invariably exhibit over their entire range of operation (eg, for the lungs, over a vital capacity).

The properties assigned to a system are dependent on the *form* of the mathematical model used to describe the system's behavior under the conditions at which the model was tested (validated). In fact, the terms "compliance" and "resistance" are often applied to the respiratory system (or its subdivisions) by analogy to linear, lumped-parameter models of other, nonbiological mechanical and pneumatic systems. However, another model can be just as valid a representation of a given system. For example, Rohrer's equation,

$$P = \mathbf{K}_1\dot{V} + \mathbf{K}_2\dot{V}|\dot{V}| \tag{2}$$

is a nonlinear equation that attempts to account for the nonlinear pressure-flow behavior exhibited by the airways over a wide range of flow.[11]

This model has 2 parameters, $\mathbf{K_1}$ and $\mathbf{K_2}$, which can be interpreted as 2 mechanical properties of the airways. Thus, depending on the model used, the parameters can be given

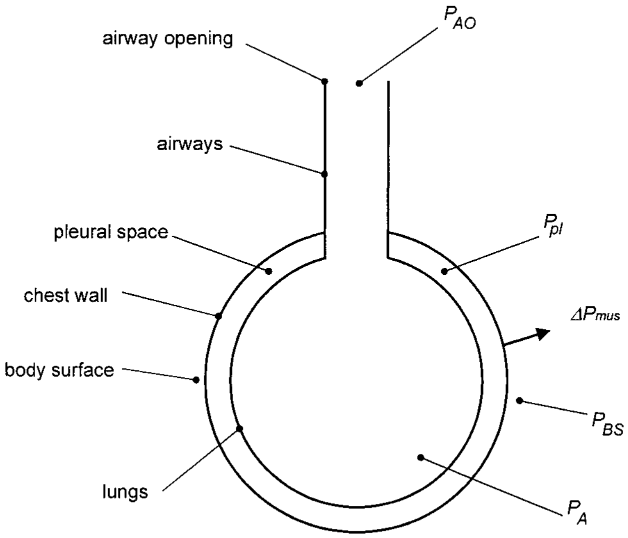

Fig. 1. Schematic representation of the respiratory system, consisting of a flow conducting tube (representing the airways) connected to a single elastic compartment representing the lungs, surrounded by another elastic compartment representing the chest wall. P_{AO} is the pressure at the airway opening, P_{pl} is pressure in the intrapleural space, P_{BS} is pressure on the body surface, P_A is alveolar pressure, and $\Delta Pmus$ is muscle pressure difference.

completely different symbols and names and interpreted as similar or different properties.

It can now be appreciated that *there is no such thing as an inherent, God-given mechanical or mass transport property of a system!* Properties arise only from a model of the system. Whereas we can always calculate a number, or a value for a given parameter, that number can be regarded as an appropriate value of a property of a system only if the model that defines the property fits the observed system behavior sufficiently well.

Subsystems

Mechanics and gas transport models have at least one thing in common. The forcing (*input*) *variable*(*s*) *are always in the form of differences between generalized forces.* In models of pneumatic mechanics, pressure differences force, or drive, volume changes and flows. In mass transport models, species concentration differences and/or partial pressure differences drive mass flows.

Here is a key concept: *the points between which the forcing variable differences are measured in a physical system define that portion of the system that is being modeled.* For example, the combination of lungs and airways (often called the pulmonary system) exists between the point at which the pressure at the airway opening is measured and the point at which the pressure on the visceral pleural surface is measured (Fig 1). Likewise, if we were able to measure a single alveolar pressure, simultaneously representative of the pressure within both lungs, then we could calculate the pressure differences between the airway opening and the alveoli and between the alveoli and the pleural space, and thereby conceptually divide, or decompose, the pulmonary system into 2 *subsystems*: the airways (everything that exists between the airway opening and the alveoli) and the lung parenchyma (everything that exists between the alveoli and the visceral pleural surface). The parameters in the models of each subsystem are the properties associated with those subsystems (eg, airway resistance and lung compliance).

With these ideas in mind, let us return to Equations 1 and 2. The only way they can make sense is if the symbol P stands for a pressure difference such as $(P_{AO} - P_{pl})$ in Equation 1 and $(P_{AO} - P_A)$ in Equation 2. If so, then "P" on the left hand side of these equations is not a very informative symbol. Likewise, if Equation 1 is a linear approximation to a small region around an operating point on a larger nonlinear relation, then the variables $(P_{AO} - P_{pl})$, V, and $\dot{V}$ should all be referenced to that operating point. Consequently, for quiet breathing around functional residual capacity (FRC), Equation 1 can be rewritten,

$$(3)\quad [(P_{AO} - P_{PL}) - (P_{AO} - P_{PL})_0] = \frac{[V - FRC]}{\mathbf{C}} + \mathbf{R}[\dot{V} - \dot{V}_0]$$

where the subscripted "0" designates the operating point, in this case the value the variable had at its starting, or resting, state; that is, $(P_{AO} - P_{pl})_0$, $V = \text{FRC}$, $\dot{V}_O = 0$). It can be recognized in Equation 3 that the terms in parentheses are differences between 2 variables measured at different points in space, the terms in brackets are changes in a variable from an operating point, and the bold letters (**R** and **C**) represent the constants (parameters) in the equation.

Characteristics

We have seen that the mechanical properties of a system are, in fact, the parameters of the mathematical pressure-volume model(s) of the system. If appropriately validated, these models describe the system response to a wide range of forcings (inputs), and their parameters are correspondingly general. However, there is another useful way to characterize a system: by documenting its *response*(*s*) *to standardized inputs under specified conditions*. An example in engineering is the step response. In respiratory physiology, the slow vital capacity-quiet breathing (spirometry) maneuver, forced vital capacity expiration, and multi-breath nitrogen washouts are examples of respiratory system responses to standardized inputs. The corresponding response curves can be described in varying levels of detail by ad hoc mathematical expressions. The parameters of these expressions can be termed *system response characteristics*. Examples of such characteristics are tidal volume, the various subdivisions of the vital capacity, forced expiratory volume in the first second (FEV_1), and closing volume.

These system response characteristics are not properties of the system in the same sense as the mechanical and mass transport properties described above. In order to relate system response characteristics to properties of the system, one would have to derive the response of the system model to the standardized forcing, and develop mathematical expressions for the response characteristic based on the model's response. These expressions will contain properties of the system and show how these are related to the response characteristics. For example, if one hypothesizes that the pulmonary airways have a collapsible region,[12] then the FEV_1 of the system during a forced expiratory maneuver (system response characteristic) could be related to the resistance of the airways downstream of the collapsible region and the compliance of the lung parenchyma. This would require developing a model that included a segmented airway.

Characteristics can also be derived for waveforms other than responses to specified inputs. Thus, arbitrary input and output waveforms can be characterized either separately (eg, peak inspiratory pressure) or in combination (eg, work of breathing). Such parameters are simply *general waveform characteristics*.

An interesting distinction exists between properties and characteristics with respect to nomenclature. Typically, the name and symbol of a response characteristic incorporates a description of the algorithm used to calculate its value (eg, FEF_{25-75}, peak flow, mean airway pressure). In contrast, properties of the system rely on their defining models as the basis for their estimation, and can be given names that are physically or functionally descriptive (eg, compliance, diffusing capacity, dead space). Nevertheless, the question remains, how do we pick meaningful names and symbols? The process is as much art as science, even though useful guidelines can be developed.

The Art

Names and symbols chosen for an entity are shorthand for all the definitions, conditions, and assumptions inherent in that entity. Thus, names and symbols can evoke large amounts of information that we subjectively associate with them. We can concisely express complicated ideas and concepts using names and symbols if the information we want these names and symbols to evoke is well known and well understood by our audience (ie, it is part of the audience's culture). A pitfall, however, is that subjective associations can differ from person to person, depending on experience and background. For example, "compliance" may mean one thing to one person (eg, a physiologist) and something completely different to another (eg, a parole officer).

One way to avoid possible ambiguities is to strictly define terms a priori and use them precisely and consistently. In this respect we can take our lead from mathematics, which conveys large amounts of information in concise symbols and terms. For example, Einstein was able to write equations for multidimensional spaces in compact form using tensor notation.

The key to success is to establish both a symbol convention and a sign convention. However, extending mathematical symbols to the life sciences has been limited to some extent in the past by the printers used by clinical and physiology journals and book publishers, whose equipment could support only limited varieties of fonts, type faces, layered subscripts and superscripts, and so forth. This should be less of a problem now with the flexibility provided by computer-based publishing.

Developing a useful sign convention and precisely defined, nonredundant symbols is no easy task. Furthermore, the precision and clarity inherent in mathematics can be diluted when symbols are translated into language and given descriptive names. Bad habits can arise when units of measure and numerical values are assigned to symbols. Just because 2 entities are numerically equal or are measured in the same units does not make them the same entity. The volume of a container is not the same variable as the change in volume of that container, even though both may be expressed in liters and at certain times may have the same numerical values. Likewise, esophageal pressure is not pleural pressure, even though, under some circumstances, changes in esophageal pressure can be shown to closely approximate the changes in pleural pressure.

To begin developing a useful nomenclature we should distinguish among the 5 entities that we have previously discussed:

1. Primary variables. In lumped-parameter models of the respiratory system, variables are conceptually associated with well-mixed compartments, not actual positions in 3-dimensional space. Observable variables are either directly measured or defined as functions of measured variables. Unobservable variables are estimated using models, measured variables, and given values of model parameters. Primary variables are expressed on an absolute scale (eg, atmospheric pressure in cm H_2O, and temperature in degrees Kelvin).

2. Difference variables. Measured or expressed as the difference between simultaneous measurements of the same variable at 2 distinct locations in the system (eg, the pressure difference between the airway opening and the pleural space).

3. Change variables. Measured or expressed as the change in a variable with respect to its value at a previous instant in time (eg, the change in lung volume during a breath relative to the volume at the start of the breath) or to a fixed reference point.

4. Properties. These are defined by the mathematical model of the system and are the parameters (constants) in the model (eg, pulmonary compliance). They are estimated using the model and sets of measured values of the model's variables. Depending on the level of detail in the model, these can be material properties, structural properties or system properties.

5. Waveform characteristics. Descriptors of waveforms of system variables. Characteristics of wave shapes observed in response to specific, controlled, standardized inputs, or forcing, of the system (eg, parameters derived for the volume-time curve during a forced expiratory maneuver, such as FEV_1, and forced vital capacity) are system response characteristics. Characteristics of wave shapes associated with arbitrary system operation are general waveform characteristics.

Respiratory nomenclature systems currently in use run into trouble because of inherent inconsistencies, including:

1. The same symbols used for different variables (P for pressure and pressure difference, V for volume and volume change)
2. The same names used for different symbols and quantities (pleural pressure used for esophageal pressure)
3. Different symbols used for the same entities (TV and VT, MMEF and $\text{FEF}_{25\text{–}75}$)
4. Different names for the same symbols and quantities (exhaled flow and exhaled minute ventilation are both given the symbol $\dot{V}_E$)
5. Definitions not model-based (transpulmonary pressure defined as $P_{pl} - P_{AO}$ instead of $P_{AO} - P_{pl}$)
6. Names not sufficiently descriptive ($\text{P}_{0.1}$)
7. Meanings of symbols are context-dependent (C for compliance, C for concentration, C for carbon, C for centigrade, C for a constant)

So how do we approach developing a nomenclature for the respiratory system? We could name a particular item whatever we want to, like parents naming their children, and, to say the least, very creative results could be achieved. We could also assign any symbol we want to that item. But for the name and symbol to be helpful they should be descriptive and hint at the nature of the item. However, if this occurs, it is a bonus. For a name and symbol to be useful we must provide a minimum of 4 things:

1. A descriptive symbol and name
2. A definition, including the underlying model, the range of values over which it applies, and any restrictions or assumptions upon which the model is based and, if required, experimental procedures and/or algorithms required for evaluation
3. A sign convention
4. Practical units of measure

We offer the following suggestions to get the process started, or as Bill Maher would say, "It's time for New Rules."[13] However these "rules" are not always hard and fast, and some exceptions may be necessary.

Symbols and Names

The general rule is that variables are italicized. Properties and characteristics are not.

1. Primary variables. Capital letters such as P (pressure), V (volume), T (temperature), Q (volume flow of a fluid), and C (concentration in a mixture). These are important in, among other things, the equation of state for gases, and in the derivation of the governing equations for the total body plethysmograph, spirometer, and gas washouts.

A. Subscripts and superscripts. The location/direction or time at which a variable is measured is designated by a subscript, usually of capital letters (eg, P_{AO} or $P_{0.1}$). (An example of an exception is small "a" representing "arterial.") Partial pressures are expressed with their gas species as a superscript (eg, P^{O_2}). A composite symbol (ie, with both subscripted and superscripted characters) can be encased in parentheses. The time at which a measurement is made can be written either as an argument in parentheses, for example, $P_{AO}(t_0)$, or as a subscript outside of the parentheses around composite symbols, $(P_A^O)_0^2$. Raising a variable to a power is done in the conventional manner, with a superscript. For a composite symbol, the superscript is located outside the parentheses enclosing the symbol. For example, $(P_A^{CO})_0^2$ stands for the square of the partial pressure of carbon monoxide in the alveoli at time zero.

B. Smaller font on same line. Capital and lower-case letters are used on the same line as the symbol they modify to identify type (versus location, as identified by subscripts) such as **VD** for dead space volume or Cdyn for dynamic compliance. A subscript can be added to identify location as in **VD**$_\mathbf{A}$ for dead space volume in the alveolar region.

C. Use lower-case letters for abbreviations (eg, "pl" for "pleural"), and upper-case characters that represent the initial letters of words (eg, "AO" for "airway opening").

D. Arguments. Enclosed in parentheses following a variable. If no argument is given, time is implied.

2. Difference variables. The difference between measurements made at 2 points in space is designated by a capital delta symbol, preceding the variable symbol. For example, $\Delta P_{TP} = (P_{AO} - P_{pl})$ should be referred to as "transpulmonary pressure difference." The "pressures" that are routinely encountered in respiratory physiology are invariably pressure differences.[14] Calculated values for terms that correspond to pressure differences should also be designated by a preceding Δ, and referred to as a pres-

Table 1A. Summary of Symbol Conventions

General Format $([\text{entity}]^{\text{substance}}_{\text{location, time index}}\ (\text{argument}))^{\text{power}}$

Entity	Subtype	Style	Examples	
Variable	Primary	Italic, upper case	P	pressure
			V	volume
			$\dot{V}$	flow
			C	concentration
			T	temperature
	Difference (difference between points in space)	Italic, upper case, delta symbol	ΔP	pressure at one point minus pressure at another point on the system
	Change (change relative to a reference point)	Italic, lower case	p	pressure measured relative to an operating point
Argument (used with variables only; if no argument explicitly stated, then time is implied)	Not applicable	Style of entity	$P(t)$	pressure as a function of time
			$v(p)$	change in volume as a function of change in pressure
			$\mathbf{Z(j\boldsymbol{\omega})}$	impedance (complex number; function of angular frequency)
Property	Material	Bold, usually Greek	$\boldsymbol{\varepsilon}$	elasticity
			$\boldsymbol{\eta}$	viscosity
	Structural	Bold, usually English	$\mathbf{C}$	compliance
			$\mathbf{R}$	resistance
			$\boldsymbol{\tau}$	time constant
			$\mathbf{I}$	inertance
			$\mathbf{D}$	diffusing capacity
	System	Bold, upper-case may be English and Greek	$\mathbf{Z(j\boldsymbol{\omega})}$	impedance (complex number; function of angular frequency)
Characteristic	General waveform	Upper and lower case	PEEP	positive end-expiratory pressure
			MAP	mean arterial pressure
			WOB	work of breathing
			PIP	peak inspiratory pressure
	System response	Upper and lower case	FEV$_1$	forced expiratory volume in the first second
			MV	minute ventilation
			FVC	forced vital capacity
			Cdyn	dynamic compliance

sure difference. For example, the elastic component of the transpulmonary pressure difference is $\Delta Pel_{TP} = (V_L - \text{FRC})/\mathbf{C}_\text{L}$ and should be referred to as "transpulmonary elastic pressure *difference*" if it must be given a name at all. Likewise, the aggregate forces developed by the respiratory muscles to produce breathing movements should be included in the pressure-volume relation for the respiratory system as a pressure difference and should be designated $\Delta Pmus$, the ventilatory muscle pressure *difference* (see Fig. 1).

3. Change variables. The difference between measurements made at 2 points in time, or a measurement made relative to a reference value, is designated by a lower-case letter. For example:

$$P_{AO}(t) - P_{AO}(t_0) = P_{AO} - P_{AO}(0) = P_{AO} - (P_{AO})_0 = p_{AO}$$

are all equivalent ways to express the change in pressure at the airway opening. Likewise,

$$(P_{AO} - P_{PL}) - (P_{AO} - P_{PL})_0 = \Delta p_{TP}$$

where Δp_{TP} is the *change* in transpulmonary pressure *difference*.

Unique situations are the change in the rate of change of volume, and the change in the volume flow of a fluid when each is measured from zero. For the former,

$$\dot{v} = \dot{V} - 0 = \dot{V}$$

Table 1B. Summary of Symbol Modifier Conventions*

Entity	Subtype	Style	Examples	Entity
Modifier (note that modifier takes on the style of the entity it modifies)	Substance	Superscript	P^{O_2}	partial pressure of oxygen
	Location/direction	Subscript	$\bar{\mathrm{P}}_{\mathrm{AO}}$	mean pressure at airway opening
			$\mathbf{R}_{\mathbf{AW}}$	resistance of the airways
			$p_a^{O_2}$	partial pressure (gauge) of oxygen in arterial blood
			$\dot{v}_E{}^{(t)}$	expiratory flow (here expressed as an explicit function of time)
	Time index	Subscript	$P_{0.1}$	occlusion pressure at 0.1 second after start of inspiration
			FEV_1	forced expiratory volume in the first second
			t_1	inspiratory time interval
			t_E	expiratory time interval
			$\boldsymbol{\tau}$	time constant
			$\Delta P_{TR,1}$	transrespiratory pressure difference at time 1
	Descriptor (inherent part of name)	Small letters (not subscripted)	Cdyn	dynamic compliance
			VD	dead space volume
			VT	tidal volume

*Symbols over entities such as bars, dots, or double dots are normal mathematical conventions.

and for the latter,

$$q = Q - 0 = Q$$

The dot above the V is a convention from calculus, indicating the derivative of volume with respect to time, *dv/dt*.

Exceptions to this convention are t which stands for time, τ, time constant, T, temperature, and θ, change in temperature.

4. Properties. Bold capital letters, such as **C** for compliance, **R** for resistance, and **VD** for dead space volume.

5. Characteristics. Both general waveform characteristics and system response characteristics are designated by sets of capital (and lower-case) letters, usually the initials of the name of the characteristic. Examples include FEV_1 (forced expiratory volume in the first second), $\bar{\mathrm{P}}_{\mathrm{AO}}$ (mean pressure at the airway opening; the bar over the P designates the mean, or average, value), PIP (peak inspiratory pressure), Cdyn (dynamic compliance), and FVC (forced vital capacity).

The symbol conventions described in this section are summarized in Table 1.

Definitions

When defining a term we navigate the 7 Cs. The definition should be:

1. Concise (simple and straightforward)
2. Clear (unambiguous)
3. Complete (no tacit meanings)
4. Conceptually correct (understand what you are defining before you attempt to compose the definition)
5. Consistent both internally (symbols, names, and definitions should correspond) and externally (with other like terms and concepts)
6. Conventional (understood, agreed upon, accepted, and acknowledged by our peers)
7. Context-independent (should not rely on context to be understood)

Sign Conventions

1. In general, there is no such thing as a negative primary variable. A perfect vacuum corresponds to $P = 0$, and while nature abhors a vacuum, it gets really annoyed when you try to go below zero pressure. You can't close down a void more than eliminating the void, so the volume within a container cannot be reduced below $V = 0$. Temperature can't be reduced below absolute zero, $T = 0°K$. And you can't have a mixture with a concentration, C, of a substance, X, less than having none of the substance in the mixture, so that $C^X \geq 0$.

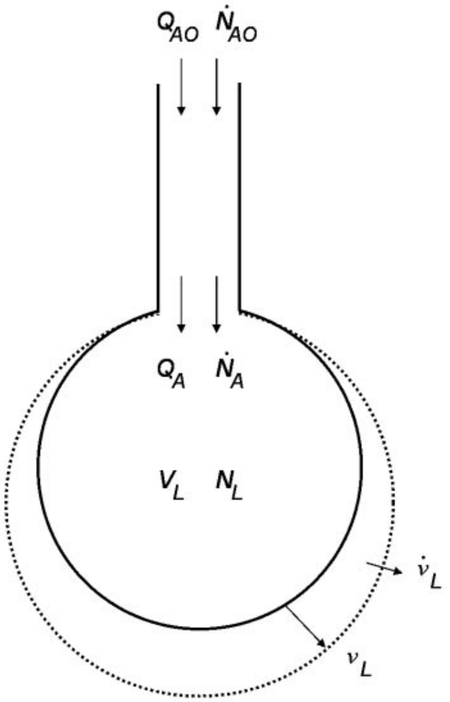

Fig. 2. Diagram of both lungs, represented as a single well-mixed compartment. *N* is the number of moles (mass of mixture divided by the molecular weight of the mixture), $\dot{N}$ is mass flow, and *Q* is volume flow of gas mixture, with the subscripts indicating location at the airway opening (*AO*) in the alveoli (*A*) and lung (*L*), respectively. The arrows point in the positive direction for each of the variables.

Exceptions to this non-negative rule are variables that are rates of change (ie, derivatives with respect to time, such as Q and $\dot{V}$). These can have positive and negative values, where the sign designates direction.

2. Both difference variables and change variables can have positive, zero, or negative values. The signs assigned to them are based on their definitions and the system models in which they are used. Thus, based on the simple models of Figures 1 and 2, we can set the following conventions.

A. Expansion of a system (container) corresponds to a positive rate of volume change, $+\dot{v}$. Compression of a container produces a negative rate of change of volume, $-\dot{v}$. (A positive *rate of volume change* will cause an increase in volume even though the *volume change* of the container relative to some fixed volume reference can still be negative, albeit increasing.)

B. A volume flow of fluid (gas or liquid) that causes an increase in the amount of a fluid (N, number of moles) in a container is positive, $+q$, and one that is in the direction out of the container is negative, $-q$. In the case of a conduit, or tube, a positive direction must be chosen a priori but should conform whenever possible to the above convention when the tube leads to a container.

C. In general, pressure differences that tend to produce a positive fluid flow or an increase in volume of a container are positive, $+\Delta P$, and those that tend to produce a negative flow or tend to compress a container are negative, $-\Delta P$.

D. Concentration differences and partial pressure differences that tend to cause transport of chemical species into a container or in the positive flow direction are positive, $+\Delta C^X$ or $+\Delta P^X$. For the opposite direction they are negative, $-\Delta C^X$ or $-\Delta P^X$.

3. Properties and waveform characteristics are generally positive constants.

Units of Measure (Ranges of Values)

Typical values of variables in appropriate units can give hints as to the type of variable we are dealing with. P is always on the order of 1,000 cm H_2O or 760 mm Hg, whereas ΔP and Δp will rarely exceed 100 cm H_2O and are usually in the range of 10s of cm H_2O. V is on the order of liters, whereas v is on the order of 10s to 100s of milliliters. $\dot{V}$ and $\dot{v}$ are measured in liters (or milliliters) per minute or per second. Q and q are also measured in liters (or milliliters) per minute or per second. T is almost always in excess of 273°K. θ is typically in the vicinity of "room temperature" to "body temperature," thus usually less than 40°C. F (mole fraction) can range from 0 to 1 in terms of moles of solute to moles of mixture. C (concentration), ΔC, and Δc are expressed in moles or mass per volume.

Application of the Approach to Some Symbols for Respiratory Mechanics

It is not our intent in this paper to present a complete revamped list of all respiratory terminology. However, Wolfe and Sorbello[7] have called attention to specific problems with the symbols and definitions of pressure variables related to respiratory system mechanics. We would like to address those problems here, basing our recommendations on the ideas presented above.

Model Variables

The variables in mechanical models generally relate forces, displacements, and rates of change of displacement. In respiratory mechanics, the corresponding generalized variables are pressure difference (force per unit area), volume (displacement times area), and the rate of change of volume. The symbols most frequently used in the literature for these variables are P, V, and $\dot{V}$, respectively.

Table 2. Some Measurable Pressures Used in Describing Respiratory System Mechanics

Name	Symbol	Definition
Pressure at the airway opening	P_{AO}	Pressure measured at the opening of the respiratory system airway (eg, mouth/nose, tracheostomy opening, or end of endotracheal tube)
Pleural pressure	P_{pl}	Pressure measured in the pleural space; changes in pleural pressure are often estimated by measuring pressure changes in the esophagus
Alveolar pressure	P_A	Pressure in the alveolar (gas space) region of the lungs
Body surface pressure	P_{BS}	Pressure measured at the body surface
Abdominal pressure	P_{ab}	Pressure inside the abdomen

Table 3. Some Pressure Differences Used in Describing Respiratory System Mechanics

Definition*	Name	Symbol
P_{AO}-P_{BS}	Transrespiratory pressure difference	ΔP_{TR}
P_{AO}-P_A	Transairway pressure difference	ΔP_{TAW}
P_{AO}-P_{pl}	Transpulmonary pressure difference	ΔP_{TP}
P_A-P_{pl}	Transalveolar pressure difference	ΔP_{TA}
P_A-P_{BS}	Transthoracic pressure difference	ΔP_{TT}
P_{pl}-P_{BS}	Transchest-wall pressure difference	ΔP_{TCW}
P_{pl}-P_{ab}	Transdiaphramatic pressure difference	ΔP_{Tdi}
P_{ab}-P_{BS}	Transabdominal-wall pressure difference	ΔP_{TabW}
Theoretical transmural (ribcase, abdominal wall, diaphragm, chest wall) pressure differences that would produce movements identical to those produced by the ventilatory muscles during breathing maneuvers	Rib cage muscle pressure difference	$\Delta P_{mus_{RC}}$
	Abdominal muscle pressure difference	$\Delta P_{mus_{ab}}$
	Diaphragmatic muscle pressure difference	$\Delta P_{mus_{di}}$
	Chest wall muscle pressure difference (chest wall includes rib cage, abdomen, and diaphragm)	$\Delta P_{mus_{CW}}$

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*Terms are defined as in Tables 1 and 2.

Difference Variables

As mentioned above, the points in space at which each of the forcing variables is measured define that portion of the system that is being modeled. Therefore, we need a way to distinguish among variables of the same type but measured at different points in the system. Traditionally, subscripts have been used for this purpose. But the first step is to have a model as reference. Although there are potentially an infinite number of models for the respiratory system, perhaps the simplest and most useful for both diagnostic (eg, pulmonary function laboratory) and therapeutic (eg, mechanical ventilation) use is a lumped parameter model that comprises a single flow conducting tube (representing the airways) connected to a single elastic compartment (representing the 2 lungs) encased in another elastic compartment (representing the chest wall) as shown in Figure 1. This model provides the conceptual framework on which specific points (regions) where measured pressures, volume, and flow can be located. Relative to Wolfe and Sorbello's observations,[7] the pressures

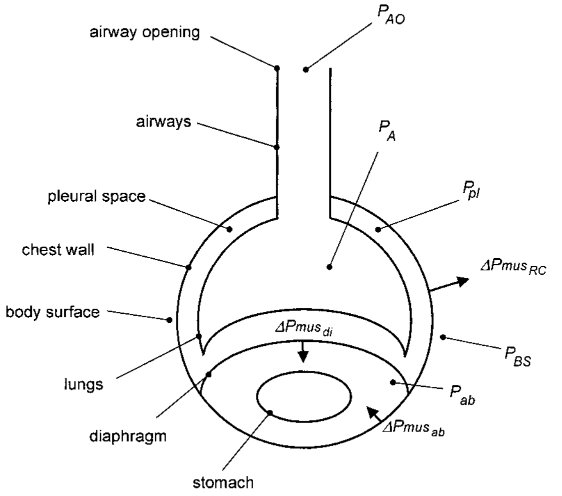

Fig. 3. Diagram of the respiratory system with one compartment lung(s) and chest wall subdivided into rib cage, diaphragmatic, and abdominal wall components.[14] The arrows labeled $\Delta Pmus$ indicate the positive directions for the corresponding muscle pressure differences. P_{AO} = pressure at the airway opening. P_A = alveolar pressure. P_{pl} = pressure in the intrapleural space. $\Delta Pmus$ = muscle pressure difference. RC = rib cage. BS = body surface. ab = abdomen. di = diaphragm.

Table 4. Symbols of Interest During Mechanical Ventilation

Name	Symbol	Definition
Plateau pressure	P_{plat}	Pressure during an inspiratory hold during mechanical ventilation
Peak inspiratory pressure	PIP	Maximum pressure during an assisted inspiration
Mean airway pressure	$\bar{P}_{AO}$	Mean pressure at the airway opening
Inspired tidal volume	V_{T_I}	Volume inspired per breath
Expired tidal volume	V_{T_E}	Volume expired per breath
Alveolar volume	V_{T_A}	Volume of alveolar gas in the tidal volume
Anatomic dead space volume	$\mathbf{VD}_{\mathbf{anat}}$	Volume of gas in conducting airways
Alveolar dead space volume	$\mathbf{VD}_{\mathbf{A}}$	Volume of gas ventilating un(der)perfused alveoli
Physiologic dead space volume	$\mathbf{VD}_{\mathbf{phys}}$	Sum of anatomical and alveolar dead space
Inspired flow	$\dot{v}_I$	Inspiratory flow relative to an operating point
Expired flow	$\dot{v}_E$	Expiratory flow relative to an operating point
Minute ventilation (expired)	MV_E	The product of expired tidal volume and ventilatory frequency
Minute alveolar ventilation	MV_A	The product of alveolar volume and ventilatory frequency
Inspiratory time	t_I	The period from the start of inspiratory flow to the start of expiratory flow
Expiratory time	t_E	The period from the start of expiratory flow to the start of inspiratory flow

at various points on the model (Table 2) are of particular interest. The pressures at these points are used to define pressure difference variables (Table 3). The difference variables then permit the decomposition of the model into its component subsystems (eg, lungs made up of airway and parenchyma, chest wall made up of rib cage and abdomen, and abdomen made up of diaphragm and abdominal wall and the contents in between) (Fig. 3). Table 4 shows terms of interest in describing mechanical ventilation.

Discussion and Conclusions

Early in my career, I (FP) attended a lecture presented by a preeminent pulmonary mechanics researcher. The subject was the phenomena associated with airway collapse at residual volume and above, at closing volume. During his otherwise lucid explanations, he kept referring to "airway opening pressure."

As a beginner in the field, I had been reading about the pressure that is measured at the mouth and/or nose, that is, at the "airway opening." This was given symbols such as P_{AO} and P_{AWO} (or, incorrectly, Patm, for atmospheric pressure, the value of the pressure at an unobstructed airway opening). These symbols were referred to, variously, as "pressure at the airway opening" and "airway opening pressure."

Consequently, throughout the lecture, whenever the speaker used the term "airway opening pressure," I had to decide whether he was referring to the airway transmural pressure difference at which the intrapulmonary airways become patent, or the pressure measured at the mouth and/or nose. It seemed that he used the term for both situations interchangeably, but it was not always clear if this were true. My only clues were contextual. Interpreting what he was saying into what he meant was a constant distraction and reduced the clarity of the lecture.

Calling a rose a rose is not difficult if the appropriate words, names, and symbols exist and are generally understood. Developing a consistent terminology is possible and need not be difficult to do. After a consensus is reached on existing terms in routine use, set up guidelines for the naming and symbolizing of new items that arise. If changes are suggested to existing terms or when names and symbols for new terms are required, they should be published so that they are understood and objections can be aired.

The most important exercise is to establish a consistent nomenclature and symbology, re-educate people in the definitions and uses of the resulting terms and symbols, and develop guidelines for new terms and symbols. This is especially important for instructors, and for reviewers and editors of journal articles and textbooks. Reviewers and editors especially should be held accountable for publishing and proliferating faulty terminology.

However, there is a fine line to be aware of. On the one hand we want to improve understanding and communication by standardizing terms and definitions. On the other, we want to leave room for improvement and expansion of ideas, not stifle creativity and not impede innovation and progress.

Thus, it is important to establish workable guidelines and not immutable rules. We must continually review and critique existing terminology while requiring logical, understandable, defensible reasons for change. Our attitude should not be that "everyone will know what I mean." Instead, we should actually say what we mean, using terms and symbols familiar to our audience. To this end it is our hope that the above discussion and suggestions will serve as impetus for dialogue in the field that will influence journal and book publishers to adopt a consistent set of conventions for the names and symbols used for respiratory-system-related terms.

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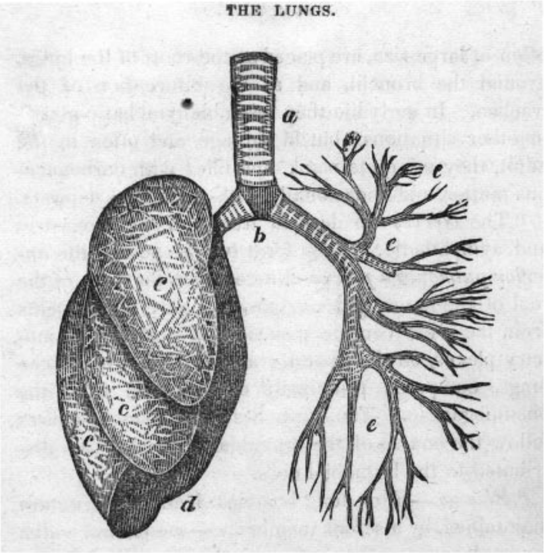

The lungs from *Consumption: Its Prevention and Cure by the Water Treatment: With Advice Concerning Haemmorrhage from the Lungs, Coughs, Colds, Asthma, Bronchitis, and Sore Throat*
Joel Shew MD, Practitioner of Water-Cure
New York: Fowler and Wells; 1854
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