Breathing, Obstruction, Restriction, and Gas Exchange: A Pulmonary Function Testing Interpretation Framework for Novice Learners

AUTHORS: Ryan E. Nelson[1,2] and Jeremy B. Richards[2,3]

[1]Section of Hospital Medicine, Beth Israel Deaconess Medical Center, Boston, Massachusetts; [2]Harvard Medical School, Boston, Massachusetts; and [3]Division of Pulmonary, Critical Care, and Sleep Medicine, Mount Auburn Hospital, Cambridge, Massachusetts

ABSTRACT

Pulmonary function testing (PFT) is a common method of assessing patients with respiratory symptoms, yet exposure to PFT is variable throughout medical training. Therefore, incorporating a dedicated approach to teaching PFT into the formal medical education curriculum can ensure that trainees become familiar with both the relevant physiologic principles involved in interpreting PFT results and the indications for performing PFT in clinical practice. In this "How I Teach" article, we present breathing, obstruction, restriction, and gas exchange (BORG), a novel, small-group workshop designed to teach novice learners a sequential framework for PFT interpretation. The BORG workshop comprises two segments: a whiteboard minilecture that illustrates the BORG framework and a case-based worksheet whereby learners apply this approach to sets of PFTs with increasing difficulty. Our workshop is grounded in two cognitive psychology frameworks: the cognitive theory of multimedia learning and the dual-process theory. We provide three figures and four supplementary videos to illustrate our workshop's design and delivery, as well as both learner and instructor versions of our BORG worksheet. Last, we address three PFT concepts that have challenged us as instructors and provide evidence-based teaching scripts. The BORG workshop can be used by medical educators working with medical students and residents as a means of helping learners progress along the continuum from a basic understanding of spirometry to independent analysis and interpretation of PFTs to application of PFT results to medical decision making.

Correspondence and requests for reprints should be addressed to Ryan E. Nelson, M.D., Hospitalist, Beth Israel Deaconess Medical Center, Instructor in Medicine, Harvard Medical School, 330 Brookline Avenue, Span 2, Boston, MA 02215. E-mail: rnelson2@bidmc.harvard.edu.

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Pulmonary function testing (PFT) is a common method of assessing patients with respiratory symptoms, and it is important for medical learners to develop an understanding of the indications for PFT and interpretation of PFTs during their training. As exposure to PFT is variable in clinical practice, incorporating a dedicated approach to teaching PFT into the formal medical education curriculum can ensure consistent exposure to relevant conceptual and clinical practice topics. Specifically, a dedicated approach to teaching PFT will allow all learners to become familiar with both the important physiologic principles involved in interpreting PFT results and the indications for performing PFT in clinical practice.

In this "How I Teach" article, we present breathing, obstruction, restriction, and gas exchange (BORG), a PFT interpretation framework for novice learners. This novel, two-part educational workshop incorporates multimedia learning, inductive clinical reasoning, and spaced learning principles to foster generative cognitive processing and promote long-term retention of foundational PFT concepts. Of note, we focus exclusively on contemporary practices for PFT interpretation, acknowledging that the expression of normal values will likely change in the next several years to a system employing *z*-scores that emphasizes a patient's differences from population-level mean values on the basis of standard deviation rather than as percentage predicted. Specifically, in this "How I Teach" article and the workshop, we use the historical definition of forced expiratory volume in 1 second (FEV_1):forced vital capacity (FVC) for obstruction and percentage predicted values for spirometry and lung volumes to define the presence and severity of disease states, as this approach to PFT interpretation is both very common in current clinical practice and conceptually easier for learners to understand. Throughout this article, we provide multiple figures to illustrate our approach, and we include both learner and instructor versions of our BORG worksheet. Importantly, this sequential approach is accessible to medical educators across disciplines, not only pulmonary and critical care attending physicians and fellows but also academic hospitalists and primary care preceptors.

WHO ARE THE LEARNERS?

The content of the BORG workshop is designed to provide novice learners, such as medical students and internal medicine residents, with an introduction to the physiologic basis and interpretation of PFTs.

WHAT IS THE SETTING?

We implement the BORG workshop as part of afternoon didactic teaching sessions for internal medicine residents and rotating medical students during their internal medicine and intensive care unit rotations. The BORG workshop is designed to introduce the fundamentals of PFT interpretation within the 30-minute time frame typical for teaching sessions within busy clinical environments, with an emphasis on sustaining attention and promoting retention (1).

WHAT IS THE APPROACH?

The BORG workshop is a two-part, small-group teaching session (Figure 1). Part 1 is an interactive whiteboard mini-lecture (WML) that illustrates the BORG framework (Figure 2). The breathing module serves as a primer to review the volumes and capacities constituting the respiratory cycle, while the obstruction,

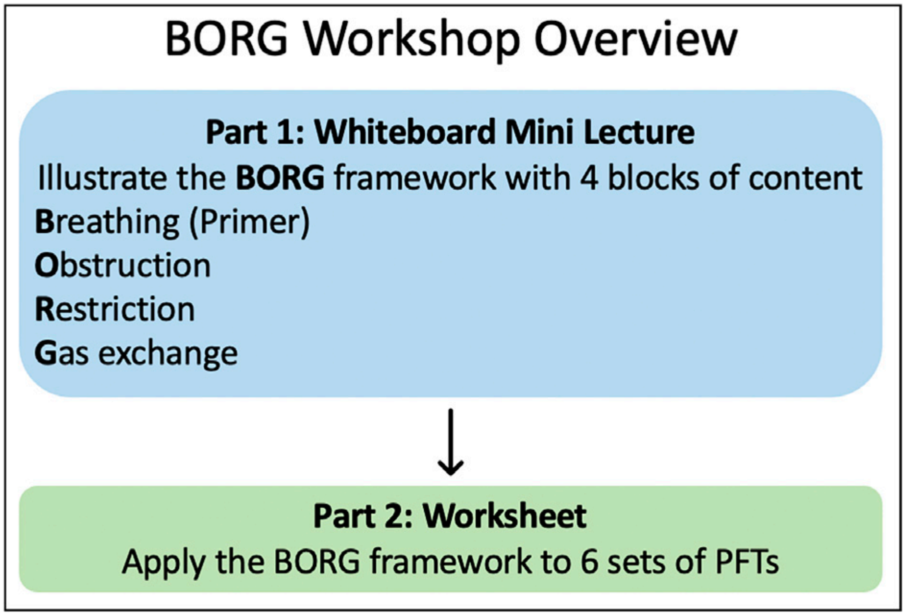

Figure 1. Breathing, obstruction, restriction, and gas exchange (BORG) workshop overview. The BORG workshop is composed of two parts: *1*) a whiteboard minilecture to illustrate the BORG framework for pulmonary function test (PFT) interpretation and *2*) a worksheet whereby learners apply this framework to PFT examples.

restriction, and gas exchange modules demonstrate a sequential approach to PFT interpretation. Part 2 is a case-based worksheet whereby learners apply the BORG framework to a series of PFTs with increasing difficulty (*see* Appendix E1 in the data supplement).

Our framework has two notable limitations owing both to its focus on novice learners and to its design to fit within a shorter time frame of 30 minutes. First, we provide at times a heuristic approach to PFT interpretation, which teaches learners a basic clinical and conceptual framework but does not delve into the nuances of advanced PFT interpretation. For example, though bronchodilator responsiveness will correctly diagnose a majority of patients with asthma, it will misclassify a small percentage of patients with chronic obstructive pulmonary disease (COPD) (2). Second, we do not routinely review flow–volume loops (FVLs) to assess the adequacy of spirometric data or to diagnose fixed or variable airway obstructions. In our experience, this prolongs the teaching session beyond 30 minutes, which can pose challenges in a busy clinical environment. When we are afforded additional time for teaching (approximately 45 min), we do include instruction on FVLs, and we encourage medical educators to do the same. Specifically, we represent these concepts on the whiteboard as the "FVL pyramid" advance organizer (*see* Appendix E3 in the data supplement) and include additional PFT sets in the case-based worksheet.

WHY IS THAT THE APPROACH?

The BORG workshop's design is grounded in two cognitive psychology frameworks: the cognitive theory of multimedia learning (CTML) (3) and the dual-process theory (4). CTML argues that "people learn better from words and pictures than from words alone" and is supported by evidence-based principles (5). The dual-process theory

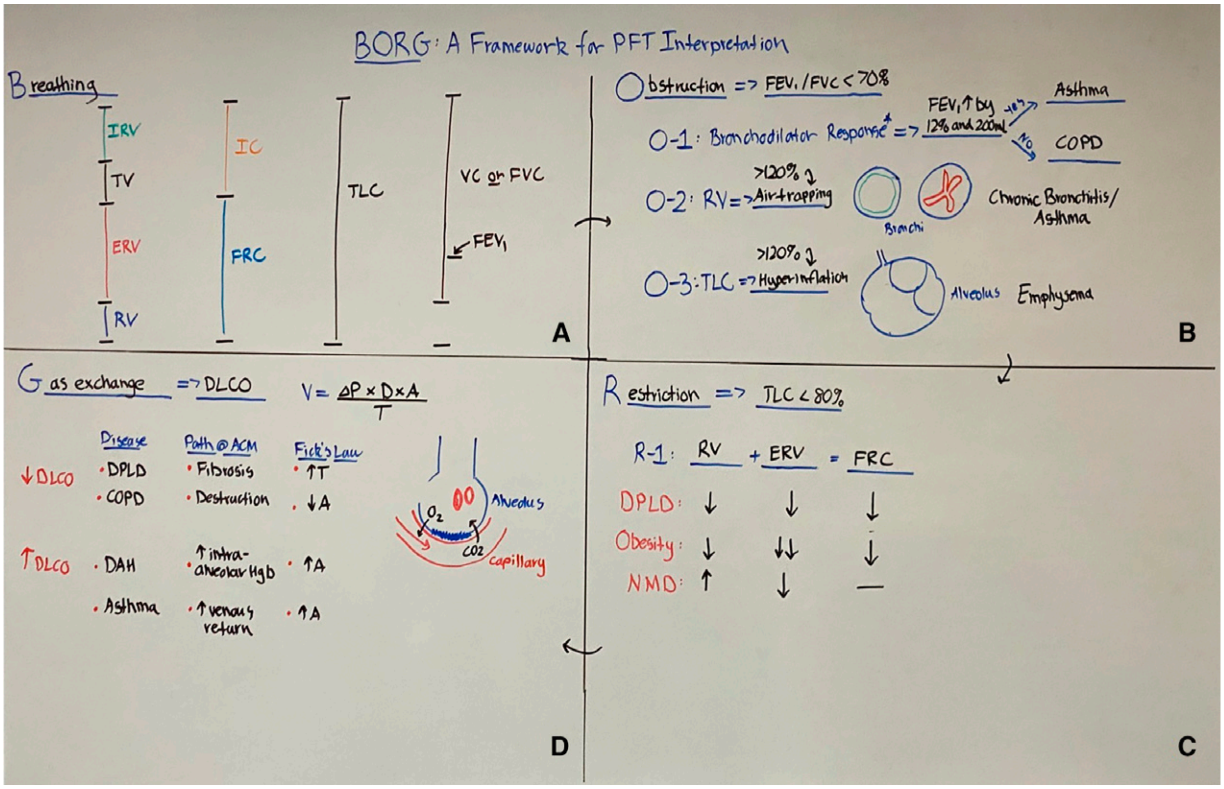

Figure 2. Breathing, obstruction, restriction, and gas exchange (BORG) workshop whiteboard minilecture (WML). Panel (*A*) is the Breathing module, panel (*B*) is the Obstruction module, panel (*C*) is the Restriction module, and panel (*D*) is the Gas exchange module. An interactive WML illustrates the BORG framework. The asterisk next to "Bronchodilator Response" denotes that this heuristic approach may misclassify a small percentage of patients with COPD who do have positive bronchodilator responses. A = surface area available for gas exchange; ACM = alveolar–capillary membrane; COPD = chronic obstructive pulmonary disease; D = diffusion coefficient of the gas; DAH = diffuse alveolar hemorrhage; D_{LCO} = diffusing capacity of the lung for carbon monoxide; DPLD = diffuse parenchymal lung disease; ERV = expiratory reserve volume; FEV_1 = forced expiratory volume in 1 second; FRC = functional residual capacity; FVC = forced vital capacity; Hgb = hemoglobin; IC = inspiratory capacity; IRV = inspiratory reserve volume; NMD = neuromuscular disease; ΔP = partial pressure difference of the gas; PFT = pulmonary function test; RV = residual volume; T = thickness of the alveolar–capillary membrane; TLC = total lung capacity; TV = tidal volume; V = volume of gas transferred across the alveolar–capillary membrane; VC = vital capacity.

posits that our brains engage two distinct cognitive pathways, an *intuitive* process that involves rapid, unconscious pattern recognition (system 1) and an *adaptive* process that requires slow, analytical, and conscious reasoning (system 2) (4).

We begin with a WML to illustrate the BORG framework. WMLs, colloquially referred to as "chalk talks," are brief, interactive whiteboard-based teaching sessions that combine written text with unique hand-drawn images (6). Learners have consistently rated WMLs as an effective and engaging teaching method (7, 8). Using horizontal and vertical lines, we divide the WML into four modules: breathing, obstruction, restriction, and gas exchange, and we include headings to clearly label each module. Dividing the whiteboard and including headings uses the segmenting and signaling principles of CTML, respectively, which contend that learning is enhanced by teaching in smaller segments and including visual cues to highlight key concepts (3).

In the breathing module, we review the respiratory cycle and basic spirometric terms. Familiarizing these terms leverages the pretraining principle of CTML, which states that cognitive processing is improved by priming learners with key terms before the main lesson (5). The primer also ensures that all learners begin the workshop on as level a playing field as possible. In the obstruction, restriction, and gas exchange modules, we combine a flowchart and two tables to illustrate our approach to PFT interpretation. Simplifying the text in this fashion with arrows, symbols, and abbreviations uses the coherence principle of CTML, which states that "learning is enhanced when unnecessary words are removed from a multimedia lesson" (5). Last, we draw and annotate graphics of the bronchi, alveoli, and alveolar–capillary membrane (ACM) in real time to leverage the multimedia principle of CTML: combining pictures with words fosters deeper cognitive processing (3).

We continue the BORG workshop with a case-based worksheet that allows learners to apply our approach to PFT interpretation and to practice clinical reasoning skills. Learners take turns evaluating a set of PFTs, and we encourage them to explain their clinical reasoning out loud to foster inductive, system 2 cognitive processing, which is a more effortful, analytic, logical approach to reasoning and cognition (4). We provide blank lines on the worksheet and encourage learners to summarize their cognitive processes and to use spaced practice several weeks after the initial session to foster retention and durability of learning.

Perhaps the most common alternative approach to teaching an introduction to PFT interpretation is with a PowerPoint (Microsoft) lecture. Yet without conscientious slide preparation, this format can increase the extraneous cognitive load and engender passive learning. Our approach is unique in that we deliberately use multiple active learning techniques and visual aids, and we combine multiple teaching activities, all of which help renew attention and sustain learner interest (9).

WHAT IS THE CONTENT?

We open the teaching session by enumerating its three learning objectives. We indicate that by the end of this workshop, learners will be able to

1. define the volumes and capacities constituting the respiratory cycle, as well as the essential components of spirometry;
2. differentiate between obstructive and restrictive lung diseases using the BORG framework for PFT interpretation; and
3. determine the expected change in diffusing capacity of the lung for carbon monoxide ($D_{L_{CO}}$) on the basis of a disease's pathophysiology at the ACM and the variable affected in Fick's law.

As previously indicated, for extended teaching sessions, we include a fourth learning objective:

4. Interpret basic FVLs using the FVL pyramid.

Part 1: WML—Illustrate the BORG Framework

Before learners arrive at the workshop, we draw the outline of the WML on the whiteboard (Figure 3). In the context of whiteboard-based learning, we refer to this prearrangement of the whiteboard as the *mise en place*, or "everything in its place," as it helps maintain an organized whiteboard throughout WML delivery and ensures that key concepts are highlighted (10). We use blue and red markers to set the *mise en place* and a black marker to fill in the content during the session itself. To maintain engagement and interactivity throughout the WML, we solicit learner participation to fill in the blanks of the *mise en place*.

At the outset of the WML, we define the BORG framework as breathing,

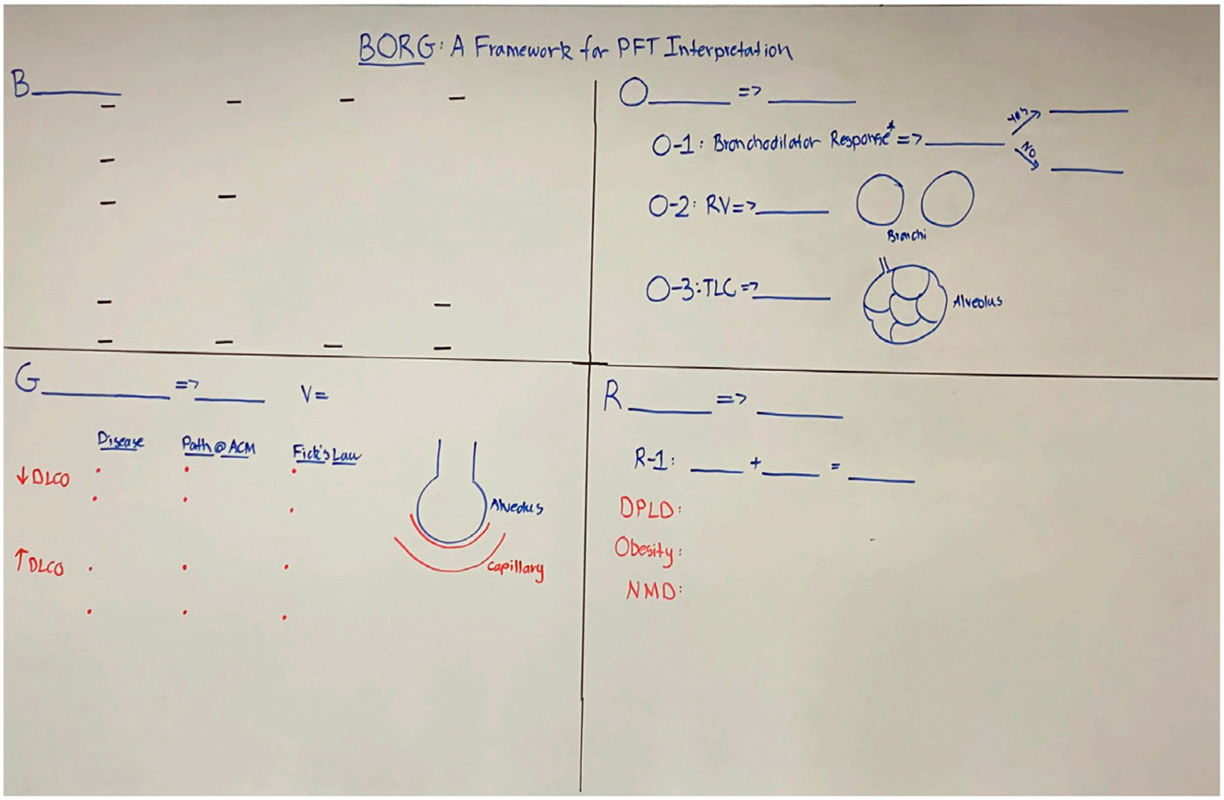

Figure 3. *Mise en place* for the BORG workshop whiteboard minilecture (WML). The *mise en place*, or prearrangement of the whiteboard, helps maintain an organized whiteboard throughout WML delivery and helps ensure that key concepts are highlighted. We use blue and red markers to set the *mise en place*. ACM = alveolar–capillary membrane; BORG = breathing, obstruction, restriction, and gas exchange; $D_{L_{CO}}$ = diffusing capacity of the lung for carbon monoxide; DPLD = diffuse parenchymal lung disease; NMD = neuromuscular disease; PFT = pulmonary function test; RV = residual volume; TLC = total lung capacity.

obstruction, restriction, and gas exchange and explain that each module should be performed in sequence on a set of PFTs to ensure a complete and accurate diagnosis. We emphasize this point by drawing arrows on the whiteboard to link the four modules, and we encourage learners to become familiar with and practice using our stepwise approach to PFT interpretation.

Breathing module (primer). The BORG workshop begins with the breathing module, a brief primer of the volumes and capacities within the respiratory cycle and the basic components of spirometry (Figure 2A). To make the respiratory cycle content more interactive, we demonstrate each measurement with our own respirations and hand gestures, draw each measurement on the whiteboard in real time, and encourage learners to mimic our breathing patterns. We show tidal volume (V_T) as the volume of air inhaled and exhaled with normal breathing at rest. We then deeply inhale, contracting the diaphragm and activating accessory muscles of inspiration, explaining that this additional inspired volume represents the inspiratory reserve volume (IRV). We define the inspiratory capacity as the sum of these two volumes. At maximal inspiration, we note that our lungs are now full, representing the total lung capacity (TLC). As we deeply and forcibly exhale, activating the accessory muscles of expiration, we label the additional volume expired after V_T as the expiratory reserve volume (ERV) and the total volume remaining in the lungs after maximum exhalation as the residual volume (RV). We note that the sum of ERV and RV represents functional residual capacity (FRC). Although these breathing patterns may seem intuitive, demonstrating the volumes and capacities in this clear and exaggerated manner helps make these concepts salient for learners.

Next, we reference how PFTs are obtained to provide further context about the mechanics of these measurements. Specifically, we demonstrate how a patient is asked to breathe comfortably and then inhale to TLC and forcibly exhale to RV to obtain FVC, which we draw on the whiteboard. We explain the concept of FEV_1 as the fraction exhaled within the first second of maximal forced exhalation from TLC. By briefly recontextualizing these volumes and capacities, key concepts of lung volume measurements and physiologic principles can be emphasized; however, a detailed review of the technical aspects of how PFT is performed is beyond the scope of this teaching session, and care should be taken to prioritize the clinical and physiologic core concepts related to PFT interpretation. We include a short video of our approach to further demonstrate this portion of the BORG workshop (*see* Appendix E4 in the data supplement).

We conclude the primer with a brief exercise to probe for learner understanding. We ask for one volunteer to demonstrate for the group V_T, IRV, TLC, ERV, and RV and another to explain FVC and FEV_1 in their own words.

Obstruction module. After this primer, we continue with the obstruction module (Figure 2B) and define obstruction as an FEV_1:FVC ratio of 70% or less than predicted. For the purposes of this teaching session, we do not introduce the concept of standard deviations and the lower limits of normal as alternative definitions of obstructive airway disease, as presenting multiple different definitions for obstruction can be confusing for learners. If obstruction is present, we proceed to substeps O-1 to O-3. In substep O-1, we review the bronchodilator challenge to assess for reversibility of airway obstruction. We explain that an increase in FEV_1 of more than 12% of predicted and of more than 200 ml demonstrates reversibility of airway obstruction and is likely consistent with asthma, whereas a lack of such reversibility is likely consistent with COPD. We include an asterisk here next to "Bronchodilator Response" to emphasize that this is a heuristic approach to bronchodilator responsiveness and may misclassify a small percentage of patients with COPD. In substep O-2, we assess RV, noting that values greater than 120% of predicted signify air trapping, which is due to incomplete exhalation of air because of airway obstruction. To illustrate this point, we annotate a graphic of two bronchi to compare a normal bronchus (left) with an inflamed, narrowed bronchus (right) that may cause air trapping as in chronic bronchitis or asthma. Last, in substep O-3, we assess TLC, observing that values greater than 120% of predicted suggest hyperinflation due to increased respiratory system compliance, resulting in overexpansion of lung tissue, as can be seen in COPD. To demonstrate the concept of emphysematous changes, we erase several alveoli from the accompanying drawing. *See* Appendix E5 in the data supplement for a short video of the obstruction module.

Restriction module. We begin the restriction module (Figure 2C) by defining restrictive lung disease as a TLC of 80% or less than predicted. If restriction is present, we proceed to substep R-1, in which we use a table to compare the direction and degree of RV, ERV, and FRC changes to differentiate among common restrictive lung diseases. We use arrows to symbolize the direction and degree of spirometric changes. For example, we note that *symmetric* reductions in RV, ERV, and FRC (one downward arrow each) suggest diffuse parenchymal lung disease, as inflammation and scarring of the pulmonary parenchyma result in a uniform decrease in lung compliance, defined as a decrease in the change in volume for any given change in pressure during the respiratory cycle. In contrast, we explain that an *asymmetric* reduction in ERV (two downward arrows) relative to the RV and FRC values (one downward arrow each) implies obesity or other chest wall pathophysiology, as changes in compliance of the chest wall can result in asymmetric changes to the overall respiratory system compliance. Finally, we show that restriction with an increased RV (one upward arrow) together with relative *preservation* of FRC (horizontal dash) and consequent decrease in ERV (one downward arrow) may signify neuromuscular disease (NMD), as neuromuscular dysfunction results in an inability to maximally leverage accessory muscles of inspiration and expiration, thereby decreasing TLC and increasing RV, respectively, without changing FRC. *See* Appendix E6 in the data supplement for a short video of the restriction module.

Gas exchange module. The final module of the BORG framework is gas exchange (Figure 2D). We define $D_{L_{CO}}$ as a measure of gas exchange at the ACM. To enhance learners' understanding of $D_{L_{CO}}$, we include a review of Fick's law and the physiology of the ACM. We explain that the volume of gas (V) transferred across the ACM is *directly* proportional to the partial pressure difference of the gas (ΔP), the diffusion coefficient of the gas (D), and the surface area available for gas exchange (A) but *indirectly* proportional to the thickness (T) of the ACM. We explain that $D_{L_{CO}}$ combines the latter three variables. We establish these concepts as the physiologic basis for the single-breath method, whereby the rate of removal of carbon monoxide (a gas whose transfer is limited almost solely by diffusion) from an inhaled gas mixture is used to calculate $D_{L_{CO}}$ (11). As we teach these concepts, we complete the equation for Fick's law on the whiteboard and reference an accompanying graphic of the ACM.

We then fill in a table to compare diseases with decreased versus increased $D_{L_{CO}}$, to describe the corresponding pathophysiology at the ACM, and to identify the affected variable in Fick's law. We note that diffuse parenchymal lung disease has decreased $D_{L_{CO}}$ because of *fibrosis*, which increases the thickness of the ACM (T with an upward arrow). We illustrate this change by drawing a thick, wavy line at a portion of the ACM on the graphic. We contrast this with COPD, which has decreased $D_{L_{CO}}$ from *destruction* of the ACM, which decreases the surface area (A with a downward arrow) available for gas exchange. We erase a segment of the ACM on the graphic to show this concept. We then review two diseases associated with increased $D_{L_{CO}}$. We explain that stable patients with diffuse alveolar hemorrhage may have increased $D_{L_{CO}}$ because of widespread intraalveolar hemoglobin, which increases the surface area available for gas exchange (A with an upward arrow), as oxygen is taken up by intraalveolar hemoglobin without having to cross the ACM (12). We draw several red blood cells within the alveolus in the graphic. Last, in asthma, D_{LCO} may be increased because of increased venous return and elevated capillary blood volume, which also increase the surface area available for gas exchange (A with an upward arrow) (13). We add a red arrow flowing into the capillary to signify these changes. *See* Appendix E7 in the data supplement for a short video of the gas exchange module.

When we have additional time for afternoon teaching (a total of approximately 45 min), we include a fifth module: the FVL pyramid. We give learners a brief break and reset the whiteboard during this time. We present introductory FVL concepts as the FVL pyramid advance organizer. *See* Appendix E3 in the data supplement for further details, including the FVL pyramid whiteboard layout.

Part 2: Worksheet—Apply the BORG Framework

Once we have illustrated the BORG framework, we distribute the BORG worksheet, comprising six sets of PFTs with increasing difficulty and complexity (*see* Appendix E1 in the data supplement). We have learners take turns applying the BORG framework to each set of PFTs. We encourage learners to share their clinical reasoning out loud with a small group of colleagues as they work through each step.

Below each set of PFTs, we provide blank spaces in which learners can write the correct answers and their supporting clinical reasoning. Instead of filling in these blanks during the workshop, we explicitly highlight the benefit of spaced repetition for long-term memory retention and encourage learners to revisit the worksheet and fill in the blanks during later, independent review (14). For extended teaching sessions, we add the FVL pyramid module and include two additional PFT sets that incorporate FVLs (*see* Appendix E1 in the data supplement, pp. 4–5). The final page of the worksheet presents a summary of the BORG framework that learners can take home for later reference. We have included the instructor version of the BORG worksheet that shows each correct PFT interpretation with supporting clinical reasoning (*see* Appendix E2 in the data supplement).

We conclude the BORG workshop with the muddiest point, an effective active learning technique that facilitates reflection (15). We ask learners "What was the 'muddiest point' from today's BORG workshop?" This practice helps us identify and clarify difficult concepts. Three challenging concepts we have faced as instructors are detailed in the next section.

WHAT CAN BE CHALLENGING?

As instructors, we have encountered three challenging concepts that required further literature review to synthesize evidence-based explanations. We frame these challenging concepts below as questions with corresponding instructor teaching scripts.

Question 1: Why is TLC reduced in NMD while the FRC value is relatively preserved?

Teaching script. In the early stages of many NMDs, the *inspiratory* muscles are primarily affected, leading to loss of IRV and therefore a reduction in TLC. In addition, inspiration is an active process, requiring diaphragmatic and potentially accessory muscle contraction, whereas expiration is typically a passive process, in which energy expenditure and muscle contraction are not needed. Interestingly, as NMDs progress, the expiratory muscles may also weaken, manifesting as an *increase* in RV, whereas TLC remains overall decreased (16). Finally, because FRC does not depend on either inspiratory or expiratory muscle contraction (it is the result of the static balance of forces between the chest wall's propensity to expand and the lungs' propensity to collapse, independent of any neuromuscular activity), it is preserved in NMDs.

Question 2: Why is ERV asymmetrically reduced compared with RV in obesity?

Teaching script. In obesity, the diaphragm is pushed upward by increased intraabdominal contents, such that its position at rest (FRC) is closer to its position at RV, compared with nonobese individuals. This can manifest as a striking asymmetric reduction in ERV compared with RV, which is relatively unaffected (17).

Question 3: Why might D_{LCO} increase in asthma?

Teaching script. The pathophysiology underlying the increased D_{LCO} often seen in patients with asthma is multifactorial. Over time, chronic inflammation leads to bronchial narrowing and increased airway resistance, which can result in increased work of breathing and inspiratory muscle contraction, causing a relative decrease in pleural pressure during inspiration and a consequent increase in pulmonary venous return. The decrease in pleural pressure essentially "pulls" more blood from the extrathoracic veins into the central venous circulation. Furthermore, increased vascularization in the lungs creates an increase in pulmonary capillary blood volume with extravasation of red blood cells into the alveoli (2, 18–20).

CONCLUSIONS

PFT interpretation can be challenging for medical learners because of idiosyncrasies of terminology, the complexity of the related physiologic and pathophysiologic mechanisms, and inconsistent exposure to PFT in clinical practice. The BORG workshop for teaching PFT to novice learners involves a theoretically grounded educational approach to help learners effectively and efficiently interpret PFTs and incorporate PFT results into their clinical reasoning. Our stepwise approach can be used by medical educators working with medical students and/or residents to help learners progress from a basic understanding of spirometry, lung volumes, and D_{LCO} measurements, through independent analysis and interpretation of PFTs, to application of PFT results to medical decision making.

Author disclosures are available with the text of this article at www.atsjournals.org.

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