The Objective Measurement of Breathlessness*

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Both direct and indirect psychophysical methods can be used to measure breathlessness. With indirect methods, detection thresholds can be defined. Direct methods are easier to apply and give more information than indirect methods. Direct methods include interval (partition) and ratio scales, which are easy to apply; both have advantages and disadvantages. The selection of scale depends largely on the question addressed. For comparison across individuals or for the measurement of absolute magnitude (however imprecise), simple category scales are adequate and useful.

Open magnitude scaling is best used to define the stimulus parameters influencing perceptual magnitude. Comparison across groups or individuals using exponents as an index of perceptual sensitivity should be interpreted with caution. Where possible, alternative methods should be used to validate differences found. The age-old bias against sensory measurement may be in part our inability to understand the sensory mechanisms and have little to do with the validity of the measurements.

Measurement is the matching of a number to an object or event according to rules, and its strength is based on the invariance with which matching occurs. The replacement of description by measurement provides a precise means of communication which allows the resolution of problems by calculation rather than by debate. It is important to bear in mind that usefulness and validity are not synonymous. Validity is based on whether the measurement conforms to the rules. However, the constraints imposed by the rules may result in a measurement which is valid but not useful; alternatively, measurement may be useful but not strictly valid. The intensity of debate and the lack of measurement are a testament to the need for the measurement of breathlessness.

PSYCHOPHYSICS

Psychophysics is the quantitative study of the relationship between sensory stimuli and the evoked sensory response. The evoked conscious sensory response is dependent on the integrated interaction of a series of unit processes, which are outlined in Figure 1. For example, in the perception of the intensity of light, the number of quanta of light energy striking the retina forms the intensity of the stimulus. This physical energy is transformed by the retinal pigments in the rods and cones, and the chemical transformation results in an alteration in electrical potential. This potential results in an impulse firing frequency in the ganglion cells, which is propagated to the optic nerve and ultimately to the occipital cortex. The impulse firing rate bears a relatively fixed mathematical relationship to the light intensity. The perceptual intensity bears a similar mathematical relationship to the magnitude of the stimulus.

Perception can be viewed as the interpretation of the sensory impression in light of previous experience and learning and is an integral component of sensation. The perception of the sensory stimulus is left to behavioral psychology. Conventional neurophysiology embraces the study of these unit processes in isolation and neglects their integrated interaction.

Psychophysics can be divided into four domains, outlined in Figure 2. The nature of the problem addressed determines the psychophysical method used. Some questions can be directly addressed, but others may have to be answered in an indirect manner because of the constraints imposed by the methods. Bridging all of these unit processes, psychophysics allows rigorous quantitative study of the relationship between the stimulus and the evoked sensory response. It is thus ideal for the study of both integrated interaction and perception.

For the remainder of this communication I will illustrate the range of these methods and how they can be used to understand the mechanism of breathlessness.

DETECTION AND DISCRIMINATION

Breathlessness is a sensation and as such is likely to share the same sensory structures and mechanisms as other respiratory sensations. Although not directly stated, the mechanism determining load detection was considered likely to share common mechanisms with breathlessness. In the early 1960s, threshold detection of small added loads to breathing was used to address the nature of the symptom of breathlessness, the origin

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Recent Advances in Management of Obstructive Airways Disease
Figure 1. Schematic diagram of the series of sequential unit processes followed in the generation of conscious sensation.

By determining the detection threshold for added resistive loads before and after vagal blockade, it was possible to conclude that the vagus was not essential for load detection. Threshold detection was normal in patients with complete cervical cord transection or spinal anesthesia to the cervical cord, leading to the conclusion that communication with the chest wall was not essential for load detection. Exclusion of the upper airway by the application of loads to the trachea (via tracheostomy) or following anesthesia of the airway left detection unchanged, suggesting that upper airway receptors could not account for detection. The exclusion of the upper airway was further supported by the reduced sensitivity for load detection in patients with airflow obstruction. Alteration in upper airway receptors would not be expected in these patients. Resistive load detection during active breathing, followed by passive ventilation using a Drinker respirator, shows that active contraction of the respiratory muscles is required for the detection of loads (Fig 3). These studies were used to address the origin of the receptors involved in load detection. Used in this manner, questions as to the origin, receptors, afferent traffic, and even the nature of breathlessness can be addressed. However, this method has limitations, and not all questions can be addressed.

Detection and discrimination thresholds are similar and share common methods. There are three classic methods for the determination of sensory thresholds: (1) the frequency method; (2) the method limits; and (3) the method of constant stimulus. The precision of these methods can be considered equivalent, and the selection of method is not a question of validity but one of ease of use. Using the conscious sensation of tidal volume, I will illustrate how the detection threshold for tidal volume could be measured using the three methods.

Frequency Method

The object of the study is to define the minimum in-resistive load detection.

Figure 2. Four basic domains used in the study of psychophysics to look at the quantitative relationship between stimulation and evoked sensory response.

Figure 3. Probability of detection for the group is plotted against the added resistance. −−−, active ventilation; ×−−, passive ventilation. Results are means ± SEM. Right, added resistance reliably detected during passive ventilation.
crease (or decrease) in tidal volume reliably detected by a subject. The subject produces a constant tidal volume (one method would be by targeting to a volume trace on an oscilloscope). A number of test stimuli are then administered. The test stimuli consist of the reference volume and the volumers bridging the detection threshold. Following the presentation of a reference tidal volume, the subject targets to a slightly bigger (or smaller) volume by altering the gain on the scope unknown to the subject—the visual target is the same. The subject is then asked to make a forced choice: Is the volume the same? ("yes" or "no"). After many trials the positive responses, expressed as a percentage of the total number of presentations for each tidal volume, are plotted against the tidal volume. The detection threshold is defined as the volume detected on 50 percent of presentations, and the percentage of positive responses for the reference volume is taken as an index of response bias. The threshold volume is conventionally expressed as a fraction of the background volume to define the Weber fraction.  

Method of Limits

The method of limits might be designed similarly. A reference volume is given, and on the next breath a slightly increased volume is presented and a forced choice made. The reference volume is repeated with a systematically increasing volume on each test breath until detection occurs. The volume continues to increase, until the presence of a stimulus is obvious to the subject (multiple positive detections). The sequence is then reversed until the subject can no longer detect the presence of an added volume. The sequences from absence to presence and presence to absence are repeated on multiple occasions and the detection threshold averaged. The reference stimulus is repeated prior to every test stimulus to avoid reliance on memory and to enhance contrast.

Constant Stimulus

The subject produces the reference volume. He is then asked to reproduce the volume. The reference volume is presented again and reproduced. The SD of the reproduced stimuli (tidal volumes) is closely related to the detection threshold. Depending on the confidence limits set, detection at 50, 75, 95 percent, etc., the SD is multiplied by the appropriate constant. A more detailed account of these methods is contained in any standard text of psychophysics.

These techniques could also be used to measure the detection threshold for breathlessness directly. Breathlessness might be induced by exercise of varying intensity, by the addition of added loads, by progressive hyperinflation, or by progressive neuromuscular block, and the threshold defined by any or all of these techniques. Differences across individuals or groups could be established. The effect of various interventions might be tested; for example, drugs or muscle training. Threshold detection is dependent on the neurophysiologic sensitivity and also on the response bias of the individual. The rigorous measurement of response bias depends on the question addressed. Signal detection theory26-28 to isolate response bias and neurophysiologic sensitivity should be performed separately where warranted. One must always beware that the questions asked are the dominant consideration, not the method. When patients appear to be excessively breathless, the intensity is often due to unrecognized respiratory muscle weakness in the presence of a breathing pattern which contributes to more rather than less breathlessness. Altered perception or response bias exists, but prior to accepting it as the cause, a close scrutiny of stimulus parameters is essential.

Scaling

Normal people are free of breathlessness at rest. During mild to moderate exercise, although ventilation increases, breathing is not perceived as unpleasant. As exercise intensity increases, breathlessness intensifies, and at maximum exercise it is perceived as severe. In patients with lung disease, this sequence of events is similar. However, the exercise intensity at which breathlessness occurs and the intensity of breathlessness at any given level of exercise is increased. Scaling breathlessness during exercise has a number of advantages. One, the appropriate intensity of breathlessness during exercise can be established, and the resultant information is helpful both in investigation and treatment. Two, the stimulus parameters contributing to breathlessness can be established.

Scaling involves the measurement of a magnitude. The specific scales are divided into nominal, ordinal, interval, and ratio, and the attributes of the individual scales are preserved as we move from nominal to ratio. The distinction between the scales is based on the rules (questions asked), shown in (Fig 4). Assuming that we can measure breathlessness reliably using these scales, their validation depends on the isolation and quantification of the stimulus. Ordinate scales have been applied to breathlessness for many years, but their usefulness is limited due to the wide variance of the measurement. Interval and ratio scales provide more information and are generally preferable.

Interval Scale

The Borg scale29-32 is an example of an interval scale. This scale ranges from 0 to 10, and has simple verbal expressions tagged to numbers such as "very, very slight" to "severe." The addition of these expressions introduces categories, but the subject is free to select any intervening number or fraction. The visual analogue
scale\textsuperscript{27} is similar, but no intervening categories are identified. The Borg scale applied to perceived exertion has been successfully used for a long time, is rugged, and is easily understood by patients. As such, the scale is ideal for clinical use. Neither this category scale nor the visual analogue (partition scales) are true ratio scales\textsuperscript{28,29}.

The following is an illustration of the kind of information that can be ascertained using sensory scaling. A large group of patients and normal subjects were asked to estimate magnitude of breathlessness during a maximum incremental exercise test (100 km/min). Within an individual subject breathlessness is initially absent and then increases as exercise intensity increases, terminating with severe breathlessness (Fig 5). With increasing airflow obstruction, the severity of breathlessness intensifies and exercise capacity decreases. Respiratory muscle effort is significantly increased in subjects terminating exercise because of breathlessness as compared to those who stop exercise due to leg fatigue.\textsuperscript{30} The differences are small and are reflected in the small perceptual differences. The major factors contributing to increased effort during exercise are the tension generated by the respiratory muscles and the velocity and extent of muscular contraction. Progressive hyperinflation is an added factor in patients with airflow obstruction.

At maximum exercise the intensity of breathlessness was similar in the presence or absence of lung disease, suggesting that the intensity of breathlessness toler-

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<tr>
<td>Ratio</td>
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\textbf{Figure 4.} Scales of measurement are shown in left column. Basic operations needed to create a given scale are listed in middle column, and typical examples of use in right column.

\textbf{Figure 5.} Exercise capacity and maximal oxygen uptake (as percent predicted) plotted against the Borg scale of breathlessness in patients and normal subjects with varying degrees of airflow obstruction.
ated by patients and normal subjects is the same. Although the subjective limitation in most patients or normal subjects is leg fatigue, the intensity of breathlessness is close to limiting intensity. We commonly attribute exercise limitation to cardiovascular, ventilatory, or peripheral neuromuscular factors, but it is the expression of these limitations as symptoms which is the proximal factor limiting exercise.

The Borg scale is basically an interval scale with some ratio properties allowing comparison of sensory intensity across groups.44 This scale, although reproducible and stable, may not be internally valid. For example, if we asked subjects to adjust the level of exercise so that the intensity of breathlessness was either doubled or halved, the exercise intensity might not precisely coincide with the values predicted from this kind of study. This discrepancy can be expected, because the subjects are confined to a closed scale and are inclined to group responses within the defined categories.4,5,31 These systematic departures from validity are compensated by the potential to compare across subjects and the indication of absolute magnitude given and are extremely useful.

The usefulness of this scale is supported by experimental studies in normal subjects. When normal subjects are progressively loaded with external elastic or resistive loads (incrementally increasing loads presented for 5 minutes' duration to maximum capacity), the maximum score of 10 coincides with the onset of respiratory muscle fatigue.38-33 During exercise, normal subjects do not develop respiratory muscle fatigue, because exercise is usually terminated due to peripheral muscle fatigue. On average, the intensity of breathlessness is scored 6 to 8 (severe to very severe). With respiratory loading combined with exercise, the intensity of breathlessness increases proportionally, and a score of 10 is reached.34

Ratio Scales

By asking subjects to estimate directly the magnitude of sensory stimuli such as light intensity, sound, taste, perceived force, etc, Stevens and others33,31 have established that man can quantify the magnitude of his sensory experience in a reliable and meaningful sense. When the magnitude of a muscle force doubles (F), the perceived or sensory magnitude (Y) increases threefold (Y = KF3.7). The nature of this relationship is known not only for muscle force but for light intensity, sound intensity, taste, thermal sensation to mention a few.35 For equal physical magnitude ratios, there are equal sensory magnitude ratios which are constant. The uniqueness of the relationship for given sensory modality has established that within certain limits of precision, man can make an accurate quantitative interpretation of his sensory experience.

In the course of these studies, it has become obvious that the stimulus must be precisely defined.33 Stimulus parameters other than intensity, contribute to the perceived magnitude. The background level of stimulation (state of adaptation), stimulus duration, stimulus frequency, and the number of receptors stimulated all contribute to perceived magnitude. Ratio scales in small numbers of subjects can be used to establish the precise relative contribution of various stimulus factors to the magnitude of the sensation. To illustrate the use and potential value of open magnitude scaling, in Figure 6 the results of an open magnitude scaling study are shown. In this study we asked a small group of normal subjects to estimate the magnitude of a series of added resistive loads, while having the subjects target to varying inspiratory flow rates. The subjects were free to select any number they felt appropriate to

![Magnitude Estimation of Added Resistance](image)

**FIGURE 6.** Top panel, group mean estimates of perceived magnitude at varying inspiratory flow rates plotted as a function of added resistance. Bottom panel, group mean estimates of perceived magnitude at varying inspiratory flow rates plotted as a function of product of flow rate and resistance; ie, peak inspiratory pressure.
match the magnitude of the load. Although the stimulus added was an external resistance, the proximal stimulus in this case proved to be the peak pressure.

Over the past several years we and others24-47 have applied these direct psychophysical techniques to elucidate the nature of breathlessness. By inducing breathlessness of varying intensity under widely different circumstances (loaded breathing, hyperinflation, exercise, weakness by partial curarization), we have been able to show that an increase in respiratory muscle effort is common to all these circumstances in which dyspnea occurs. The perception of this effort appears to explain quantitatively the intensity of breathlessness. Although the quality of the sensation is widely different in these circumstances, breathlessness is always proportional to effort. This relationship suggests that the patient in pulmonary edema—dyspneic at rest—and the normal subject at maximum exercise have a comparable intensity of breathlessness. The factors contributing to this breathlessness are different, but in both cases excessive respiratory muscle effort is common.

One must be aware of the limitations of open magnitude estimation. 27 One, the exponent quantifies the increase in sensation as the stimulus increases and not the absolute magnitude of the stimulus. When the exponent is higher in one group than another, it does not imply that the perceived magnitude is greater. Two, the exponent has not been validated in individuals, but only in groups. Three, the stimulus must be carefully controlled to ensure that it remains constant before assuming that differences in the exponent mean that perception is altered. Four, the range of stimulation should be constant and embrace as much of the range as possible. For example, with perceived force or effort the physical range may cover 100 percent of the range for one subject or group and 50 percent for another, depending on individual strength. It is advisable to study the total range if possible. Marks, 31 a psychophysicist experienced in the use of open magnitude scaling, states that "it is best used in defining the parameters of stimulation," and it is wise to heed his council.

The effort required to maintain ventilation is dependent on the strength of the respiratory muscle, the velocity and degree of shortening of the inspiratory muscle, the frequency of force generation, and the duty cycle. These factors all contribute to breathlessness to a varying extent from patient to patient. Where they are measured, approximately 70 percent of the intensity of breathlessness can be explained by these factors alone. 48 Through the use of psychophysical scaling, much has been learned about the nature of breathlessness and respiratory sensation. This once obscure sensation can be measured, and its importance is not limited to the clinical assessment of breathlessness. The magnitude of respiratory muscle effort is the major contributor to distress, and to avoid this distress, a pattern of breathing is selected. Although efficiency, work, force etc. are minimized, this is achieved by reductions in sensation. An understanding of sensation is essential to the comprehension of respiratory control in conscious man and animal.

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DISCUSSION

Dr. Sackner: I recall at the last ATS meeting that your group presented two papers on the ratios of \( P_{\text{A}} \) to maximum inspiratory pressure at FRC and mean inspiratory flow during breathing to maximum inspiratory flow as dyspneic indices and you didn't discuss these at all. Are you still using these indices?

Dr. Killian: My patients dislike swallowing esophageal balloon catheters for estimation of intrapleural pressures and it is not from want of encouragement. Therefore, we decided to analyze simple parameters during exercise testing because we believe that exercise testing is under-utilized and simplification would increase its role in evaluation of breathlessness. We measured symptoms by the Borg scale during exercise to ascertain their appropriateness. We reasoned that with maximum effort, a maximum inspiratory pressure is developed which produces maximum flow in the system. By expressing the mean inspiratory flow generated during exercise as a proportion of maximum inspiratory flow, this would take into account all of the factors that I mentioned in my talk, ie, force-velocity, length-tension and respiratory muscle strength. In fact, this simple index, mean inspiratory flow/maximum inspiratory flow, is probably the most useful noninvasive index of breathlessness and correlates well to the Borg scale.

Audience: What is the role of the vagus nerve in mediating breathlessness?

Dr. Killian: The only definitive way to answer your question is to study patients who have had lung transplantation. I cannot give you convincing data that the vagus nerve is unimportant, but I believe that patients with lung transplants would also experience breathlessness.

A patient with pulmonary edema and a normal subject at maximum exercise are both intensely breathless, but the quality of the sensation is not exactly the same. That is equally true if a normal subject breathes through an external resistance at rest. The quality of the sensation is different than when exercising at a higher level of ventilation. Nonetheless, the intensity of breathlessness correlates with effort despite the obvious qualitative differences in the sensation itself. Therefore, the vagus nerve may influence the quality of the breathlessness and perhaps its intensity, but in an indirect manner, as Dr. Altose has indicated. The pattern of ventilation will change after vagal blockade and this alteration will affect motor output and sense of effort.

Audience: When you did the experiments where you induced skeletal muscle paralysis, you were dyspneic. I would have expected that you would have been less dyspneic because you blocked afferents from the respiratory muscles.

Dr. Killian: You have brought up a very controversial issue. The sense of effort is dependent on some input from the contracting muscle. If you are totally paralyzed, and there is no afferent input from the muscle, you abolish your sense of effort. There might be input from the muscle itself, but what constitutes that input is not known.