PULMONARY FUNCTION TESTS IN CLINICAL AND OCCUPATIONAL LUNG DISEASE

Edited by

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FOREWORD

Whenever a medical book is published, the proper questions are, does the medical profession need it, and what new information does it offer? Over the past four decades when pulmonary function testing has increasingly flourished (after a century's hiatus), usable guides have been slow to appear. Each pulmonary function laboratory had its own guidelines and techniques. Only recently with the recommendations produced by the American Thoracic Society have the equipment and procedures become more standardized. Still remaining are the determination of the best tests and agreement on reference values for normal population groups. The latter is the more formidable task because of the variation among different ethnic groups, equipment, procedures, and especially the variation from the average even among the so-called normal subjects.

This book does not provide final answers to these questions. It does, however, make two major contributions. First, it offers insight into current methods and applications of the maturing discipline of pulmonary function testing. Second, the book has a unique epidemiologic perspective that is applicable both to general clinical medicine as well as to the burgeoning field of occupational lung disease. Thus, it will aid those interested in assessing the respiratory physiologic status of an *individual* as well as those concerned with evaluating and categorizing *groups* such as industrial employees.

It is logical that the writers have addressed in detail how to distinguish between normal and abnormal pulmonary function test values. For this purpose, they have examined how these reference values were derived. Ideally, comparison of the person's serial test results over time is preferable to comparison with a predicted mean test value. Too often, the predicted value is the only one available to the physician for comparison, so it is critical to have dependable prediction values. Longitudinal studies are urgently needed to evaluate currently available prediction standards based on cross-sectional investigations. The longitudinal studies will also aid in disability evaluation by determining impairment from prolonged occupational exposure to noxious agents separate from the aging process alone.

To answer the opening question, this book then fills a need of physicians interested in learning how to best use the facilities now available in modern pulmonary function laboratories. Further, the book fulfills its promise to provide new information. The new role of the computer in aiding pulmonary function testing, the value of testing as an epidemiologic tool, and determination of physiologic impairment and occupational disability are several examples of valuable additions to our existing knowledge.

A hope of many concerned with chronic pulmonary diseases is that pulmonary function testing will be more widely used in clinical medicine. By targeting those at risk, especially cigarette smokers and those exposed to environmental air pollution, early diagnosis of lung airway and parenchymal disease may be possible at a more treatable stage. In the interests of cost control, such testing can consist of spirometry with maximum expiratory flow curves. This book provides useful information for spirometry as well as more complex testing.

The founder of pulmonary function testing, the Reverend John Hutchinson, designed an improved spirometer, established normal standards for the vital capacity, and tested several thousand English persons of assorted occupations. I believe this book would reserve his blessing albeit a question from him as to why it took 140 years for it to appear.

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PREFACE

This book is directed at the physicians overseeing the pulmonary function laboratories of hospitals or clinics. These physicians are responsible for the validity of the tests and for their interpretation, but may not have the resources and the expertise of an academic medical center at their disposal. Often, they are the only physicians in their institutions or in their communities who are trained or who have an interest in respiratory physiology. They need not be specialists in pulmonary medicine since pulmonary function tests are extremely important to such diverse specialities as allergy, anaesthesiology, epidemiology, internal medicine, pediatrics, and occupational medicine.

Because it is practical and clinically oriented, this book also will be of interest to medical students, clinicians-in-training, general practitioners, internists or non-pulmonary specialists who wish to learn about the application of pulmonary function tests. Reflecting the importance of pulmonary function tests in the epidemiology of lung disease and in occupational medicine (a large part of which is lung disease), sections are addressed to the physicians, environmental scientists, and attorneys working in these areas. These include chapters on regression analysis for predictive equations, reference values, disability evaluation, and epidemiologic considerations, as well as frequent references to occupational diseases such as asbestosis, asbestos-induced pleural fibrosis, other pneumoconioses, byssinosis, and occupational asthma.

This book is not intended as a laboratory manual or cook book of test procedures. This is not to minimize the usefulness of such a manual. Several references[1–4] provide detailed descriptions of pulmonary function tests. However, the procedures prescribed in a manual are always influenced by those the author has used and become familiar with in his or her own laboratory. The expansion in technology and available instrumentation provides many acceptable ways to obtain equally valid test results. For example, spirometry can be performed using wet or dry spirometers or any one of a number of integrating flow meters; results can be manually calculated from the curves or electronically calculated from analog or digital data. *No single manual can cover the enormous variety of acceptable techniques*. In addition, the continuing development of instrumentation and automation will render any manual outdated in a brief time. The need will remain, however, to understand the tests and to interpret and apply them appropriately.

Additionally, this book is not an encyclopedic text of respiratory physiology on the one hand nor an outline of lecture notes or workbook for medical students on the other. Nor is it a compendium of the latest research techniques. This book is intended as a practical guide to the clinician-physiologist to the uses and limitations of pulmonary function tests, the definition of adequate tests, and the interpretation and reporting of results. What do such terms as "normal" or "abnormal," "impaired," "restrictive," or "obstructive" mean? How do we obtain "predicted values," how do they vary in normal subjects, and how should they be used to decide whether an abnormality exists in an individual patient or a group of subjects at risk?

We hope to cover the range of pulmonary function tests. Some will be simple tests that have been in existence for many years and have received little attention of late, but that can provide useful information (the peak flow rate, maximum voluntary ventilation, breathing reserve ratio, and tidal spirogram for dynamic air trapping). Others will be at the interface between the research laboratory and the clinical testing facility (the chapters on small airway tests, lung mechanics, and provocational agents and those on newer clinical applications of pulmonary function tests including exercise, respiratory muscles, ventilatory control, and sleep problems). Our overriding concern will be with the tests in widest use and of greatest value to the clinician and epidemiologist (spirometry and flow–volume curves, lung volumes, diffusing capacity, arterial blood gases, and gas exchange).

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ABBREVIATIONS AND TERMINOLOGY

The terminology and abbreviations of the American College of Chest Physicians/American Thoracic Society (ACCP/ATS) joint committee have generally been used, following the practice of Clausen in 1982. A dash above any symbol ($\bar{X}$) indicates a mean value; a dot ($\dot{X}$) indicates a rate. In accordance with practice in the United States, traditional units are used instead of Standard International units.

Additional abbreviations (set off by parentheses) are used in this book for convenience. In tribute to long usage, such terms as *MMF* and *PFR* are used interchangeably with $FEF_{25-75\%}$ and $\dot{V}max$, respectively. Similarly, *cc* and *mm Hg* are used interchangeably with *ml* and *Torr*. The FEV_1/FVC ratio is shown as a decimal (eg, 0.75) rather than a percentage (75%) to avoid confusion with FEV_1 as a percentage of predicted. The spectrum of chronic obstructive lung disease is referred to as *CAO* for chronic airways obstruction and that of interstitial lung disease as ILD.

A modification of the guidelines for rounding off values suggested in 1973 by the European Coal and Steel Community is useful:

1. Maximum volumes > 2 L are rounded off to the nearest 50 ml, eg, VC recorded as 4.863 L becomes 4.85 L.
2. Maximum volumes < 2 L are rounded off to the nearest 10 ml.
3. Tidal volumes, minute volumes, O_2 consumption, and CO_2 production are rounded off to the nearest 10 ml.
4. MVV is rounded off to the nearest liter.

A	Alveolar
a	Arterial
(ACCP)	American College of Chest Physicians
an or anat	Anatomic
(AT)	Anaerobic threshold
ATPD	Ambient temperature and pressure, dry
ATPS	Ambient temperature and pressure, saturated with water vapor at these conditions
(ATS)	American Thoracic Society
aw or AW	Airways
B	Barometric
b	Blood
(BD)	Bronchodilator, bronchodilitation
BTPS	Body temperature, ambient pressure, saturated with water (vapor pressure 47 mm Hg at 37°)
C	A general symbol for compliance, volume change per unit of applied pressure; also, content
c	Capillary
C/V_L	Specific compliance of the lung

(CAO)	Chronic airways obstruction
(CC)	Closing capacity
C_{dyn}	Dynamic compliance, compliance measured at point of zero gas flow at the mouth during active breathing. The respiratory frequency should be designated; eg, $C_{dyn}40$
C_{st}	Static compliance; measurements made during interruption of air flow
(CV)	Closing volume; also coefficient of variation
D	Dead space or wasted ventilation (used as qualifying symbol, eg, V_D)
D	Diffusing capacity
D_k	Diffusion coefficient or permeability constant as described by Krogh: $DL \cdot (P_B - P_{H_2O})/V_A$
D_m	Diffusing capacity of the alveolar capillary membrane (STPD)
D_L(CO or O_2)	Diffusing capacity of the lung expressed as ml (STPD) of gas uptake per mm Hg alveolar-capillary pressure difference per minute. A modifier is used to designate the technique, eg, D_LCO_{SB}, D_LCO_{SS}
D_L/V_A	Diffusion (STPD) per unit of alveolar volume (BTPS)
E	Expired
(ecg)	Electrocardiograph(ic), electrocardiogram
(EPP)	Equal pressure point; see R_{us}
ERV	Expiratory reserve volume; the maximal volume of air exhaled from the resting end-expiratory level
est	Estimated
(ET)	End-tidal
f	Respiratory frequency per minute
F	Fractional concentration of a gas
FEF_{max}	The maximal forced expiratory flow achieved during an FVC (see PFR)
FEF_x	Forced expiratory flow after x portion (in percent or L) of the FVC has been exhaled; eg, $FEF_{75\%}$ is the instantaneous flow after 75% of the FVC has been exhaled. Note difference from volume designated for $\dot{V}_{max}$
$FEF_{25-75\%}$	Mean forced expiratory flow during the middle half of the FVC (formerly called the maximum mid-expiratory flow rate or MMF[R])
$FEF_{200-1200}$	Mean forced expiratory flow between 200 ml and 1200 ml of the FVC (formerly called the maximum expiratory flow rate or MEF[R])
FET_x	The forced expiratory time for a specified portion of the FVC; eg, $FET_{95\%}$ is the time required to deliver the first 95% of the FVC and $FET_{25-75\%}$ is the time required to deliver the $FEF_{25-75\%}$
$FEV_{(t)}$	Forced expiratory volume, (timed). Times (in seconds) are designated by subscripts, eg, $FEV_{0.75}$, FEV_1, etc.
FIF_x	Forced inspiratory flow. As in the case of the FEF, appropriate modifiers are used to designate the volume at which flow is measured.

FRC	Functional residual capacity; the sum of RV and ERV; the volume of air remaining in the lungs at the resting end-expiratory position
(F-V)	Flow–volume (curve)
FVC	Forced vital capacity
G	Conductance, the reciprocal of R
G_{aw}/V_L	Specific conductance, expressed per liter of lung volume at which G is measured (also referred to as SG_{aw})
(HR)	Heart rate
I	Inspired
IC	Inspiratory capacity; the sum of IRV and V_T
(ILD)	Interstitial lung disease
IRV	Inspiratory reserve volume; the maximal volume of air inhaled from the end-inspiratory level
L	Lung
max	Maximal
MBC	Maximum breathing capacity
(MEF[R])	See $FEF_{200-1200}$
(MEFV)	Maximum expiratory flow–volume (curve)
(MET)	See $FET_{25-75\%}$
(MMF[R])	See $FEF_{25-75\%}$
MVV	Maximal voluntary ventilation. The volume of air expired or inspired during repetitive maximal respiratory effort, expressed in L/min
p	Physiologic; also, probability
P	Pressure, blood or gas
(PA)	Pulmonary artery; also posteroanterior
(PC) or (PD)	Provocative concentration or provocative dose; the dose of an agent used in bronchial provocation testing that results in a defined change in a specific physiologic parameter. The parameter tested and the percent change in this parameter are indicated, eg, PD_{20} FEV_1 for a 20% decrease in FEV_1
(PDS)	Physiologic dead space; see V_D
PEF (or PFR)	Peak expiratory flow or peak flow rate, generally measured with a peak flow meter
pl	Pleural
(P max_E or P_E max)	Maximum expiratory pressure at the mouth (measured at or near TLC)
(P max_I or P_I max)	Maximum inspiratory pressure at the mouth (measured at or near RV or FRC)
P_{st}	Static transpulmonary pressure at a specific lung volume; eg, P_{st}TLC is static recoil pressure measured at TLC (maximal recoil pressure)
Q	Blood volume
$\dot{Q}$	Blood flow
R	A general symbol for resistance, pressure per unit flow; also, the respiratory exchange ratio in general, $\dot{V}CO_2/\dot{V}O_2$

R_{aw}	Airway resistance
(RB)	Rebreathing
RQ	Respiratory quotient
R_{us}	Resistance of the airways on the alveolar side (*upstream*) of the point (EPP) where intraluminal pressure equals Ppl, measured during maximum expiratory flow
RV	Residual volume; that volume of air remaining in the lungs after maximal exhalation. The method of measurement should be indicated.
S	Saturation
(SA)	Small airway
(SB)	Single breath
(SD)	Standard deviation
(SEE)	Standard error of the estimate
(SS)	Steady state
STPD	Standard conditions; temperature 0°C, pressure 760 mm Hg, and dry (0 water vapor)
t	Time
T	Tidal
TGV	Thoracic gas volume; the volume of gas within the thoracic cage as measured by body plethysmography
(TV)	Tidal volume
uao	Upper airway obstruction
V	Gas volume. The particular gas as well as its pressure, water vapor, and other special conditions must be specified in text or indicated by appropriate qualifying symbols
$\dot{V}$	Gas volume per unit time, eg, ventilation in L/min; also, rate of gas flow
v	Venous
$\bar{v}$	Mixed venous
$\dot{V}_A$	Alveolar ventilation per minute (BTPS)
Vc	Pulmonary capillary blood (preferably Qc) in intimate association with alveolar gas
VC	Vital capacity
$\dot{V}CO_2$	Carbon dioxide production per minute (STPD)
$\dot{V}_D$	Ventilation per minute of the physiologic dead space (wasted ventilation), BTPS, defined by the following equation: $\dot{V}_D = \dot{V}_E(PaCO_2 - P_ECO_2/PaCO_2 - P_ICO_2)$
V_D	The physiologic dead-space volume defined as $\dot{V}_D/f$
V_Dan	Volume of the anatomic dead space (BTPS)
$\dot{V}_E$	Expired volume (usually of *ventilation* (per minute) (BTPS)
$\dot{V}_I$	Inspired volume (usually of *ventilation* (per minute) (BTPS)
$Viso\dot{V}$	Volume of isoflow; the volume above RV at which the expiratory flow rates become identical when flow–volume loops performed after breathing room air and helium–oxygen mixtures are superimposed

$\dot{V}O_2$	Oxygen consumption per minute (STPD)
$\dot{V}_{max}X$	Forced expiratory flow, related to the total lung capacity or the absolute volume of the lung at which the measurement is made. *Modifiers refer to the amount of lung volume remaining when the measurement is made*. For example: $\dot{V}_{max}75\%$ is instantaneous forced expiratory flow when the lung is at 75% of its TLC; $\dot{V}_{max}3.0$ is instantaneous forced expiratory flow when the lung volume is 3.0 L. Note difference from volume designated for FEF.
V_T	Tidal volume; TV is also commonly used

Blood-Gas Measurements

Abbreviations for these values are readily composed by combining the general symbols defined above. The following are examples:

$PaCO_2$	Arterial carbon dioxide tension
$C(a\text{-}\bar{v})O_2$	Arteriovenous oxygen content difference
CcO_2	Oxygen content of (pulmonary end) capillary blood
F_ECO	Fractional concentration of CO in expired gas
$P(A\text{-}a)O_2$	Alveolar-arterial oxygen pressure difference; $A\text{-}aDO_2$ and $\Delta(A\text{-}a)PO_2$ has been used
SaO_2	Arterial oxygen saturation of hemoglobin
$\dot{Q}_s$	Shunt flow (total venous admixture) defined by the following equation: $$\dot{Q}_s = \frac{CcO_2 - CaO_2}{CcO_2 - C\bar{v}O_2} \cdot Q$$ Often expressed as a fraction of total flow.
$P_{ET}O_2$	PO_2 of end tidal expired gas
$(TCPO_2)$	Transcutaneous PO_2

CONTENTS

III. *REPORTING TEST RESULTS*

IV. *APPLICATIONS*

SECTION I

Introduction