CHAPTER OUTLINE

BIOGRAPHY: WILLEM EINTHOVEN
CASE STUDY: CHRONIC OBSTRUCTIVE PULMONARY DISEASE
PERSPECTIVE: ECG INTERPRETATION
PERSPECTIVE: VO_{2peak} OR VO_{2max}?

RESEARCH HIGHLIGHT: ACCURACY OF VO_{2max} PREDICTION EQUATIONS IN OLDER ADULTS
RESEARCH HIGHLIGHT: RELIABILITY AND INTENSITY OF THE 6-MINUTE WALK TEST IN HEALTHY ELDERLY SUBJECTS
Willem Einthoven was born on May 21, 1860, in Semarang on the island of Java in the former Dutch East Indies (now Indonesia). He entered the University of Utrecht as a medical student in 1878, intending to follow in his father’s footsteps. However, he began to develop in a different direction. After being assistant to the ophthalmologist Herman Snellen, Sr. in the renowned eye hospital, he made two investigations, both of which attracted widespread interest. The first was carried out after Einthoven had gained his “candidaat” diploma (approximately equivalent to the BSc degree), under the direction of the anatomist W. Koster, and was entitled “Some Remarks on the Elbow Joint.” Later he worked in close association with the physiologist Franciscus Cornelis Donders, under whose guidance he undertook his second study, which was published in 1885 as his doctor’s thesis, “Stereoscopy By Means of Color Variation.” That same year, 1885, he was appointed successor to Adriaan Heynsius, professor of physiology at the University of Leiden, which he took up after having qualified as general practitioner in January 1886. His inaugural address was entitled “The Theory of Specific Energies.” His first important research in Leiden was published in 1892: “On the Function of the Bronchial Muscles Investigated by a New Method, and on Nervous Asthma,” which was a study of great merit, mentioned as a “great work” in Nagel’s Handbuch der Physiologie (Handbook of Physiology). At that time he also began research into optics. Some publications in this field were: “A Simple Physiological Explanation for Various Geometric-Optical Illusions” (in 1898), “The Accommodation of the Human Eye” (in 1902), and “The Form and Magnitude of the Electric Response of the Eye to Stimulation by Light at Various Intensities” (with William Adam Jolly in 1908).

Another opportunity came when he began the task of registering accurately the heart sounds using a capillary electrometer. With this in view, he investigated the theoretical principles of this instrument and devised methods of obtaining the necessary stability and correcting mathematically the errors in the photographically registered results due to the inertia of the instrument. Having found these methods, he decided to carry out a thorough analysis of Augustus D. Waller’s electrocardiogram, a study which has remained classic in its field.

This investigation led Einthoven to intensify his research. To avoid complex mathematical corrections, he finally devised the string galvanometer, which did not involve these calculations. Although the principle in itself was obvious, and practical applications of it were made in other fields of study, the instrument had to be made more precise to make it usable for physiologists, and this took 3 years of laborious work. As a result of this, a galvanometer was produced which could be used in medical science as well as in technology; an instrument which was incomparable in its adaptability and speed of adjustment.

He then, with P. Battaerd, took up the study of the heart sounds, followed by research into the retina currents with Jolly (begun earlier with H.K. de Haas). The electrocardiogram itself he studied in all its aspects with numerous pupils and with visiting scientists. It was this last research which earned him the Nobel Prize in Physiology or Medicine for 1924. In addition to this, the string galvanometer has proved to be of the highest value for the study of the peripheral and sympathetic nerves.

In the remaining years of Einthoven’s life, problems of acoustics and capacity studies came within the sphere of his interests. The construction of the string phonograph (1923) could be considered a consequence of this.

Einthoven possessed the gift of being able to devote himself entirely to a particular field of study. (His genius was actually more orientated toward physics than physiology.) As a result, he was able to make penetrating inquiries into almost any subject that came within the scope of his interests and to carry out his work to its logical conclusion.

Einthoven was a great believer in physical education. In his student days, he was a keen sportsman, repeatedly urging his comrades “not to let the body perish.” He was President of the Gymnastics and Fencing Union and was one of the founders of the Utrecht Student Rowing Club. His first study on the elbow joint resulted from a broken wrist suffered while pursuing one of his favorite sports, and during the somewhat involuntary confinement his interest was awakened in the pro- and supination movements of the hand and the functions of the shoulder and elbow joints.

The string galvanometer has led countless investigators to study the functions and diseases of the heart muscle. The laboratory at Leiden became a place of pilgrimage, visited by scientists from all over the world. For this, suffering mankind has much to owe to Einthoven. In electrocardiography the string galvanometer is the most reliable tool. Although it has been superseded by portable types and by models utilizing amplification techniques used in radio communication, cardiograms from the string galvanometer have remained the standard of reference in numerous cases to this day.

Einthoven was a member of the Dutch Royal Academy of Sciences, the meetings of which he hardly ever missed. He frequently took part in the debates himself, and his sharp criticism frequently found weaknesses in many a lecture.
CASE
Mary, a part-time receptionist (61-year-old woman, weight 56.4 kg, height 165 cm) has a history of chronic obstructive pulmonary disease (COPD), asthma, and orthostatic hypotension. She is on dipyridamole, tamoxatrin, imipramine, albuterol, and theophylline. She has an age-adjusted maximum heart rate (HR) of 159 beats per minute (bpm).

DESCRIPTION
Patients with COPD have difficulty in the exhalation phase of ventilation, and their exercise capacity is limited by the pulmonary system. Mary was given a stress test to evaluate her functional status. She has a history of 45 pack-years of smoking, but she quit 8 years ago. The results of the stress test are shown below:

Resting electrocardiogram (ECG): normal sinus rhythm; resting blood pressure (BP): 132/72; resting HR: 104 bpm; resting respiratory rate (RR): 16 br·min⁻¹; protocol: cycle ergometer

Resting pulmonary function test (PFT): forced vital capacity (FVC), 1.70 L (56%); forced expiratory volume (FEV₁), 0.65 L·s⁻¹ (26%); FEV₁/FVC, 38%; maximum voluntary ventilation, 17.8 L·min⁻¹

Post-exercise PFT: FVC, 1.51 L (49%); FEV₁, 0.58 L·s⁻¹ (23%); FEV₁/FVC, 38%; the exercise ECG was normal. The test was terminated due to leg fatigue.

INTERVENTION
The maximal HR and O₂ were 79% and 44% of predicted maximal values, respectively. It is evident that exercise produced a bronchospastic response when PFT is compared before and after exercise. Reviewing the arterial blood gas variables also demonstrates that oxygenation decreased with exercise. Mary’s functional aerobic capacity is formally documented as: 2.9 metabolic equivalents at an HR of 125, BP of 138/82, VO₂peak of 17.5, normal ECG response to exercise, but with moderately severe pulmonary limitations. Peak workload was 45 watts.

The patient’s actual maximal values were far lower than predicted maximal values as a result of moderately severe ventilatory and diffusional limitations. At this level of function, Mary has difficulty doing activities of daily living. She clearly is suited for a phase III cardiopulmonary rehabilitation in which she will be given an exercise program designed to improve her level of physical fitness.

<table>
<thead>
<tr>
<th>Time (W)</th>
<th>Workload (W)</th>
<th>HR (br·min⁻¹)</th>
<th>BP (mm Hg)</th>
<th>RR (L·min⁻¹)</th>
<th>E (L·min⁻¹)</th>
<th>O₂ (PaO₂/PaCO₂/pH)</th>
<th>MET</th>
<th>ABG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rest</td>
<td>0.0</td>
<td>108</td>
<td>130/75</td>
<td>16</td>
<td>1.0</td>
<td>55/37/7.45</td>
<td>1.0</td>
<td>55/37/7.45</td>
</tr>
<tr>
<td>1:00</td>
<td>25.0</td>
<td>118</td>
<td>138/82</td>
<td>19</td>
<td>12.5</td>
<td>0.38</td>
<td>2.0</td>
<td>41/45/7.35</td>
</tr>
<tr>
<td>2:00</td>
<td>40.0</td>
<td>120</td>
<td>123/82</td>
<td>19.5</td>
<td>16.5</td>
<td>0.53</td>
<td>2.7</td>
<td>41/45/7.35</td>
</tr>
<tr>
<td>2:20</td>
<td>45.0</td>
<td>125</td>
<td>123/82</td>
<td>23.8</td>
<td>17.5</td>
<td>0.57</td>
<td>2.9</td>
<td>41/45/7.35</td>
</tr>
</tbody>
</table>

ABG, arterial blood gas variables; BP, blood pressure; E, HR; heart rate; MET, metabolic equivalents; RR, respiratory rate.
ECG Interpretation

Therapists and exercise physiologists may have access to patients’ electrocardiograms (ECGs) from the medical records in the acute care setting and often will be involved in ECG monitoring in other settings. Knowledge of ECG interpretation is therefore essential. ECG interpretation is made relatively simple if you follow a systematic method and analyze all 12 leads. The following features are important:

- Standardization (calibration) marks and technical quality
- Heart rate
- Rhythm
- PR interval
- P wave size
- QRS width
- QT interval
- QRS voltage
- Mean QRS electrical axis
- R wave progression
- Abnormal Q waves
- ST segments
- T waves

Make sure the standardization marks are present and are 10 mm tall. Check for limb lead reversal. Heart rate should be calculated to check for tachycardia or bradycardia. In doing this, make sure there is a P wave with every QRS complex to check for heart block. The rhythm is usually one of the following three: normal sinus rhythm or a sinus variant, sinus rhythm with ectopic beats (atrial premature beats or premature ventricular contractions), or a nonsinus mechanism is in play, such as atrial fibrillation or flutter, ventricular tachycardia, or an atrioventricular (AV) junctional rhythm. The PR interval should be 0.12 to 0.2 seconds in duration to rule out first-degree AV block or Wolff-Parkinson-White pattern. The P wave should be greater than 2.5 mm high and less than 3 mm wide in all leads. The width of the QRS complex is \( \leq 0.1 \) second in all leads. The QT-interval duration is related to heart rate, as shown in the table below. Notice that as heart rate increases, QT interval shortens.

### THE RELATIONSHIP OF HEART RATE TO QT INTERVAL

<table>
<thead>
<tr>
<th>Heart rate (beats per minute)</th>
<th>QT interval upper normal limits (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0.50</td>
</tr>
<tr>
<td>50</td>
<td>0.45</td>
</tr>
<tr>
<td>60</td>
<td>0.42</td>
</tr>
<tr>
<td>70</td>
<td>0.40</td>
</tr>
<tr>
<td>75</td>
<td>0.38</td>
</tr>
<tr>
<td>80</td>
<td>0.37</td>
</tr>
<tr>
<td>90</td>
<td>0.35</td>
</tr>
<tr>
<td>100</td>
<td>0.34</td>
</tr>
<tr>
<td>120</td>
<td>0.31</td>
</tr>
<tr>
<td>150</td>
<td>0.25</td>
</tr>
</tbody>
</table>

The QRS voltages should be checked, and any abnormally tall amplitudes should be noted. The mean QRS electrical axis should be estimated. R-wave progression in the chest leads should be noted. Abnormal Q waves should be noted as indicative of old myocardial infarction. ST segments should be noted for deviations from the isoelectric line. T waves should be inspected for their polarity.

Once these features are analyzed, you can formulate an overall interpretation into a list of notable findings and an interpretive summary. The ECG serves as an essential tool for the therapist and exercise physiologist to assess a patient’s readiness for and response to exercise.
Taken at face value, these terms appear to be synonymous, but their use is actually at the heart of a debate within exercise physiology concerning the validity of the concept of \( \dot{V}_O^2 \text{max} \). The debate is over whether a true plateau in \( \dot{V}_O^2 \) is achievable as the defining criteria for the \( \dot{V}_O^2 \text{max} \) point. Evidence points to the fact that only about 40% of healthy subjects ever achieve the plateau criterion, a percentage that is greatly decreased in sedentary or diseased individuals. Yet the plateau criterion has been used since the 1920s as the defining characteristic of the \( \dot{V}_O^2 \text{max} \) point. This paradigm following the work of Hill (1) has been challenged in a series of debates presented in the exercise physiology literature against (2–4) and for (5,6) this concept. While this book will not extend the debate, the debate itself brings up interesting problems with nomenclature, i.e., is \( \dot{V}_O^2 \text{peak} \) or \( \dot{V}_O^2 \text{max} \) the correct term? Robergs contributed to this discussion by arguing that both terms, \( \text{peak} \) and \( \text{max} \), are valid concepts (7). The difficulty lies in the ability to actually measure the \( \dot{V}_O^2 \text{max} \) in subjects unwilling or unable to exercise hard enough to achieve a true maximal aerobic power, which requires the subject to exercise to true volitional fatigue. Clearly if the well-established criterion of a plateau is not reached, the term peak should be affixed. In research studies requiring the documentation of true maximal effort, that effort must be objectively verified by the established criteria presented in the text. Anything short of these criteria requires that the researcher or clinician use the term peak as representative of high effort but not an objectively verifiable maximal effort. The types of individuals who will more than likely give peak but not max effort are children, sedentary people, and those with acute or chronic illness.

References

RESEARCH SUMMARY

Knowledge of patients’ aerobic capacity helps guide physicians’ medical decisions. Therefore, it is desirable that clinicians be able to accurately estimate $V\dot{O}_{2\text{max}}$. This necessity is acute given the large reported numbers of older adults being referred for stress testing. However, there is a dearth of research validating prediction equations in older adults. Rather, it has been the custom to employ the popular American College of Sports Medicine (ACSM) equations, designed to estimate steady-state $V\dot{O}_{2\text{max}}$ response as a means to also estimate $V\dot{O}_{2\text{max}}$. For example, $V\dot{O}_{2\text{max}}$ can be estimated from treadmill ergometry by using the final speed and grade from the stress test and applying this to the ACSM walking equation. However, this practice is suspect because these equations have been shown to overestimate $V\dot{O}_{2\text{max}}$. Overestimations are likely caused because the ACSM equations assume that a steady-state $V\dot{O}_{2\text{max}}$ has been reached, which is not the case in the final stage of the maximum exercise test. In fact, the stated purpose of the ACSM equation is to predict $V\dot{O}_{2\text{max}}$ responses only during submaximal, steady-state exercise. Therefore, the function of the Foster equation is to reduce the overestimations produced by the ACSM equation.

Mean differences between measured and estimated $V\dot{O}_{2\text{max}}$ of men and women were not significant for the Foster equation but were significantly different ($P < 0.05$) for the ACSM equation. Foster’s difference for men and women was approximately 2 mL·kg$^{-1}$·min$^{-1}$ less than the ACSM equation in both sexes. The ACSM equation tended to overpredict $V\dot{O}_{2\text{max}}$ with a greater discrepancy as fitness levels increased, but the Foster equation was not biased towards over- or underprediction of $V\dot{O}_{2\text{max}}$ in men and women across fitness levels.

IMPLICATIONS FOR FURTHER RESEARCH

The Foster equation produces accurate estimations of $V\dot{O}_{2\text{max}}$ in older, healthy subjects. This study design should be duplicated in clinical populations (i.e., cardiac or pulmonary) and in younger individuals to determine its validity of use for these groups. Also since the original $V\dot{O}_{2\text{max}}$ values were determined using a ramp treadmill protocol designed to produce small incremental changes in metabolic requirements, it would be interesting to see if these same results would appear if $V\dot{O}_{2\text{max}}$ was determined with the Bruce protocol. The Bruce protocol is more universally accepted, is a continuous protocol designed to elicit steady state between each stage, and produces large incremental changes in metabolic requirements.


**RESEARCH SUMMARY**

The 6-minute walk test has gained popularity in clinical settings because of its ease of use. All that is required to perform the test is a premeasured, level hallway, stopwatch, and specific instructions. It serves as a safe alternative to VO\(_{2}\max\) testing to assess functional exercise capacity in subjects such as the elderly and those with various chronic disorders. This study was designed to determine test reliability on successive days and on the same day (morning and afternoon), and to test healthy elderly subjects’ relative exercise intensity during test performance.

To accomplish the goals of the study, 12 healthy subjects aged 60 to 70 years were recruited to perform two maximal treadmill exercise tests (test 1 was used to familiarize subjects and exclude them if necessary) and five 6-minute walk tests on 3 days, 1 to 2 days apart. Mean VO\(_{2}\max\) was 30.1 ± 1.0 mL·kg\(^{-1}\)·min\(^{-1}\) and mean maximal heart rate (HR\(_{\text{max}}\)) was 152.0 ± 4.0 beats per minute (bpm) during treadmill testing. The walk tests were performed in an 18-meter long hospital corridor. Subjects walked back and forth unaccompanied at a regular pace covering as great a distance as possible during the allotted time; rest stops were allowed. Standardized encouragement was given every 30 seconds. The mean distance of the 12 subjects increased by 45.3 meters over the five trials. During testing, subjects carried the Cosmed K4 portable metabolic measurement system to record cardiorespiratory measurements (VO\(_{2}\max\) and HR\(_{\text{max}}\) during maximal testing and mean VO and HR during the walk tests). Testing over these days was arranged in such a way as to evaluate daily reliability of the 6-minute walk test and relative intensity during the 6-minute walk test (compared against VO\(_{2}\max\), HR\(_{\text{max}}\), and HR\(_{\text{reserve}}\)).

The walk tests proved to be submaximal in intensity but higher than the subjects’ ventilatory thresholds determined during maximal treadmill testing. Distance, walking speed, and VO were only lower during the first two walk tests. The results indicate that there is a good reliability of the 6-minute walk test. Using multiple predictors to estimate VO\(_{2}\max\) produced a significant correlation of 0.97. The final equation was

\[
\text{VO}_{2\text{max}} = 2830.6 - (45.2 \times \text{Age}) + (4.70 \times \text{Weight}) + (12.3 \times \text{Height}) + (1.75 \times \text{Distance}) + (0.309 \times \text{VO}) - (12.4 \times \text{HR})
\]

VO and VO\(_{2}\max\) (mL·min\(^{-1}\)), age (years), weight (kg), height (cm), distance (m), and HR (bpm).

**IMPLICATIONS FOR FURTHER RESEARCH**

The study used a small sample size of 12 healthy elderly subjects (both men and women) walking in a corridor requiring multiple laps. The equation generated in the study to predict VO\(_{2}\max\) from anthropometric values and walk test parameters is therefore, limited and in need of validation in a larger sample of similar subjects. Further, these procedures should also be tested in patient groups to determine if the regression equation developed in the study sample is applicable to others.
AUTHOR'S QUERY

[AQ1: Please confirm the name of this medication. Could it be tamoxifen? If tamoxatrin is a brand name, please change to the generic.]
[AQ2: Please provide definition for “E”.]