Comparison on Measurement Method of Maximal Oxygen Uptake during Cardiac Stress Test

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Abstract—**Cardiac stress test is a method to overview an individual's heart functional capacity by exerting stress on the heart with physical activities such as walking, running, cycling and many more. The result is measured in term of maximal oxygen uptake (VO_{2MAX}) with several options of measurement method. The options include direct testing, indirect testing (Bruce protocol, Modified Bruce protocol and Naughton protocol) and self-testing method (The Rockport Fitness Walking Test, Cooper Test and Heart Rate Ratio Method). This paper compares the available methods based on the equipment used, procedure, cost, and the suitability of each method based on the patient's condition. The result of direct testing precisely describes the heart condition meanwhile the indirect testing and self-testing method is interpreted in term of metabolic equivalents (METS). Finally, it can be deduced that direct testing can be used for a severe heart problem's patient and indirect testing and self-testing is more suitable for early and mid-detection of heart problem. The stress test is important for early detection, enables the doctor to evaluate and prognosis the patient's heart and suggests the best medication and alternative method to cure the patients.**

Index Terms—**Cardiac Stress Test; Maximal Oxygen Uptake (VO_{2MAX}); Measurement Method; Metabolic Equivalents (METS).**

I. INTRODUCTION

Cardiac stress test is an evaluation method practice by the cardiologist in order to review a patient's cardiac condition. Generally, the cardiac stress test is done for cardiac disease symptom detection, disease severity, testing the patient's functional capacity and follow up examination on the medical effect and surgical therapy given to the patient. Specifically, the cardiac stress test was performed to diagnose the presence of heart disease. Based on the diagnosis, the specialist will determine the prognosis or the risk present in assessing the severity of the disease. Only then, the specialist will be able to come out with therapeutic prescription and test the adequacy of the therapy [1].

The method was developed based on the demand-supply relationship of the heart [2]. The outcome of the relationship is produced in term of heart rate measurement. The "Demand side" represented by the blood pressure meanwhile predomination of coronary arteries perfused during diastole represents the "Supply side" [2]. Blood pressure is appointed as "Demand side" because it requires the heart to reach the demanded level for optimum heart's operation. On the other hand, "Supply" side normally determined by gradient between Diastolic Blood Pressure (DBP) and Right Atrial Pressure (RAP) multiple with

Smooth Muscle Tones (SMT) as it plays an important role in supplying blood to the coronaries [2].

Even though anyone of any age can be possibly diagnosed with cardiovascular disease, the American College of Sport Medicine developed a recommendation outline prior of cardiac exercise testing. The recommendation is based on Table 1. The recommendation consists of a classification of the low, moderate and high risk group, which is determined by the age, gender and number of risk factor. In this context, the risk factors include the history of coronary artery disease, major symptoms of cardiac disease and known cardiac disease.

Table 1
Recommendation of cardiac exercise testing [1]

Risk	Sex	Age	Risk Factor
Low	Male	<45 years old	Less than 1 risk
	Female	<55 years old	(exempted screening)
Moderate	Male	>45 years old	More than 2 risks
	Female	>55 years old	(recommendable screening)
High	Male & Female	Any age	Known CVD, pulmonary and metabolic (diabetes) disease (recommendable screening)

The recommendation can be used as a guideline to determine or recommend the activity level for screening. The activity levels are classified into three levels which is low, moderate or vigorous, and the level is quantified in term of metabolic equivalents (METS). A MET is defined as resting metabolic rate where amount of oxygen consumed at rest, sitting quietly on a chair is approximately 3.5 ml $O_2/kg/min$ (1.2 kcal/min for a 70kg person) [3]. Based on the definition, the low intensity activity is within 1-4 METS and it is recommendable for training stimulus for individual with functional capacity below 6 METS [3]. On the other hand, moderate intensity is within 5-8 METS or 40 to 60 percent of VO_{2MAX} which is more suitable for training stimulus for patients or elderly individual. High intensity is 8 METS and above or more than 60 percent of maximal oxygen uptake (VO_{2MAX}) [3]. The recommendation was developed in order to precisely determine the severity of cardiac disease with precaution.

The output of the cardiac stress test is determined by VO_{2MAX}. There are several methods used to determine VO_{2MAX} namely direct testing, indirect testing and self-testing. Each option offers various testing protocols, such as indirect testing, which consist of Bruce protocol, Modified Bruce protocol and Naughton protocol [4] and self-testing method which consist of The Rockport Fitness Walking Test, Cooper Test and Heart Rate Ratio Method. Each of

the mentioned method will be discussed extensively in the following section.

II. MEASUREMENT METHODS

A. Direct Testing Method

Direct testing method was labeled as the most reliable method to measure VO_{2MAX} precisely [5, 6]. This is because the oxygen inspiration and carbon dioxide exhalation measurement is done along the process of intended physical activity. Generally, the treadmill or stationary bicycle is used as an ergometer. An ergometer is any equipment or device used to quantify the workload and define an individual functional capacity based on the workload. It also simultaneously allowed the observant to observe and record the changes in the workload intensity [3]. Therefore, ergometer is used to trigger the stress on the heart and the workload in either the speed or gradient form will be increased gradually yet limited by the individual's maximum functional capacity as precaution [7]. The VO_{2MAX} is measured by using a spirometer along the process. Spirometer is an oxygen and carbon dioxide analyzer with a mask connected to the breathing tube. The patient wears the mask and the measurement is taken before, along and at the end of the test.

B. Indirect testing method

This method differs with direct method by implementing protocols in the test. There are several protocols existed. In this section, the explanation will cover three commonly use protocol namely Bruce Protocol, Modified Bruce Protocol and Naughton Protocol. A protocol is a set of procedure where the equipment varies gradually in term of speed or inclination of equipment stage by stage. The difference is clear as the protocol executed along with the time taken for the particular protocol to complete and bear in mind that the indirect testing will not give a precise VO_{2MAX} because this method only provides an estimation value of VO_{2MAX}. Generally, the method involves the use of ergometer, a monitor, an electrocardiogram (ECG) recorder and a stopwatch [1].

i. The Bruce Protocol

The Bruce Protocol was invented by Robert A. Bruce in 1963 and it is widely used by the cardiologist to examine the patient till this day [8]. The protocol requires the use of a stopwatch and a treadmill as ergometer. The protocol consists of nine stages with gradually increasing speed and the gradient is increased by 2 percent for each stage. The duration of each stage is three minutes before the speed and inclination of the treadmill are increased [8]. Besides, the METS value incremented by 2 METS as shown in Table 2 as follows:

Table 2
Details on Bruce Protocol stages [2]

Stage	Speed	Grade (%)	METS
1	1.7	10	5
2	2.5	12	7
3	3.4	14	9
4	4.2	16	11
5	5.0	18	13
6	5.5	20	15
7	6.0	22	17
8	6.5	24	19
9	7.0	26	21

When the test is completed, the estimation value of VO_{2MAX} is calculated based on Equation (1) for male or Equation (2) for female.

$$\text{Men} = 14.8 - (1.379 \times T) + (0.451 \times T^2) - (0.012 \times T^3) \quad (1)$$
$$\text{Women} = 4.38 \times T - 3.9 \quad (2)$$

where: T= Total time on the treadmill measured as a fraction of a minute (i.e.: 8 minutes 30 second equal to T= 8.5)

ii. The Modified Bruce Protocol

The Modified Bruce Protocol is originated from the Bruce Protocol. Slight modifications are done because the procedure in Bruce Protocol requires patient to start running directly without any chances to warm up or get familiar with running on the treadmill first. Therefore, modification is done by maintaining number of stages but for the first two stages, the patient is allowed to have a warming up session for two minutes. The original Bruce Protocol is implemented at the third stage till the ninth stage [2]. The standard estimation as Equation (1) and (2) are used to get VO_{2MAX} value.

iii. The Naughton Protocol

The Naughton Protocol is slightly different with the above protocols. This is because, instead of running, patients who undergo the test are required to walk on the treadmill. Besides, the duration for each stage only takes two minutes to be completed and the grade is constantly increased by 3.5 percent for each stage after first stage is completed [9]. The details of stages, speed, gradient and METS are shown in Table 3 as follows:

Table 3
Details on Naughton Protocol Stages [9]

Stage	Speed	Grade (%)	METS
0	1.0	0.0	1.6
1	2.0	0.0	2.0
2	2.0	3.5	3.0
3	2.0	7.0	4.0
4	2.0	10.5	5.0
5	2.0	14.0	6.0
6	2.0	17.5	7.0

As a precaution, if the patient showing any sign of ST-segment depression or arrhythmias, the test will be eliminated. This precautionary is applied for all indirect testing method to ensure subject's safety. The test is conducted stage by stage until the subject reaches the point of exhaustion. Normally, this protocol is executed to confirm the symptom of ischemia in a patient. Study has shown that the protocol is able to detect ischemic abnormalities as soon as six weeks after a heart attack [9]. Standard estimation of Equation (1) and (2) are used to calculate estimation value of VO_{2MAX}.

C. Self-Testing Method

The self-testing method allows patient to collect the needed information by themselves. The collected data is then interpreted by using respective equation depending on which test is being used. Each test uses its own equation, but the final estimation value of each test is referred to the standard table as shown in the following section. Self-Testing method provides only the estimation value of

VO_2MAX and the procedure can be done anywhere without using expensive equipment or confine space.

i. The Rockport Fitness Walking Test

The Rockport Fitness Walking Test (TRFWT) contains a very simple procedure. Subjects are required to walk as fast as possible, but not running on a one-mile track or a distance of approximately 1.6 kilometers [10,11]. Subjects then need to record their final heart rate using a heart rate monitor and the duration of completing the test by using a stopwatch. If there is no heart rate monitor available, subjects are suggested to use palpation method to get the heart rate by counting the heart rate from the carotid or radial artery for one minute after 15 second of completing the test. Based on the collected information, subjects may calculate their estimated value of VO_2MAX by using Equation (3) [10, 11]:

$$\text{VO}_2\text{MAX} = 132.853 - (0.0769 \text{ x BW}) - (0.3877 \text{ x A}) + (6.315 \text{ x G}) - (3.2649 \text{ x T}) - (0.1565 \text{ x HR}) \quad (3)$$

where: BW = Body weight (pound)
  A = Age
  G = Gender (F = 0, M = 1)
  T = Time to walk one mile (minute)
  HR = Heart rate

ii. Cooper Test

The Cooper Test is an estimation formula introduced by Dr. Kenneth Cooper to overcome the problem of unavailability of patient to attend a test for determining their VO_2MAX in a lab [12]. The test was created during 1960s to test VO_2MAX of air force soldier. The test requires subject to run at any distance non-stop for as long as 12 minutes. The test keeps the time constant while the distance is varied. When the test is completed, the distance is measured and VO_2MAX is estimated by using the Equation (4) [12]:

$$\text{VO}_2\text{MAX} = \frac{(D-504.9)}{44.73} \quad (4)$$

where: D = Distance run during 12 minutes in meters

iii. Heart Rate Ratio Method

This method is one of the self-testing methods that requires the use of expensive equipment. A subject is required to warm up on a treadmill for 10 minutes with appropriate selection of speed and gradient. The warm up is done to set the initial heart rate at 140 beats per minute. When the initial heart rate is achieved, the test started by setting the initial speed at 13 kilometers per hour (km/h) and gradually increase 1 km/h per minute with the slope simultaneously increase for 2 percent per minute. Normally, the test only last for a maximum of 10 minutes with pulmonary gas exchange and heart rate is continuously monitored [14]. For the next 48 hours after the test completed, the subject is restricted from high intensity training and the heart rate at rest (HR_{rest}) is taken in the morning of the day after test for 5 minutes while on bed. Meanwhile, the maximum heart rate (HR_{max}) is obtained by taking the last 5 second average readings of heart rate during the treadmill test [14]. Based on the obtained value and known body mass (BM) of the subject, the estimation value of VO_2MAX can be calculated by using Equation (5) [14]:

$$\text{VO}_2\text{MAX} = 15.0 \text{ ml}.min^{-1} \times \text{BM (kg)} \times \frac{HR_{max}}{HR_{rest}} \quad (5)$$

III. CARDIAC FITNESS RESULT

Each of the mentioned method gives a value of VO_2MAX and the unit was expressed in $ml/kg/min$. The value given by indirect testing method is compared to the cardiovascular fitness in Table 4 and self-testing method result is compared to cardiovascular fitness rating in Table 5 to classify the patient's cardiac condition. However, the most precise VO_2MAX value is provided by direct testing as the maximum oxygen uptake is being measured by sophisticated machine named gases analyzer [5, 6].

On the other hand, the indirect testing method provides an estimation value of VO_2MAX. The indirect testing methods mentioned here use Equation (1) to estimate the VO_2MAX value. Those values will be compared to the cardiovascular fitness classifications based on VO_2MAX as shown in Table 4. If a 44 years old male patient showing 23.4 $ml/kg/min$ of VO_2MAX, therefore he is classified in Fair group of cardiovascular fitness.

Table 4
The Classification of Cardiovascular Fitness [15]

Sex	Age	Poor	Fair	Average	Good	Great
Men	≤29	≤24.9	25-33.9	34-43.9	44-52.9	≥53
	30-39	≤22.9	23-30.9	31-41.9	42-49.9	≥50
	40-49	≤19.9	20-26.9	27-38.9	39-44.9	≥45
	50-59	≤17.9	18-24.9	25-37.9	38-42.9	≥43
	60-69	≤15.9	16-22.9	23-35.9	36-40.9	≥41
Women	≤29	≤23.9	24-30.9	31-38.9	39-48.9	≥49
	30-39	≤19.9	20-27.9	28-36.9	37-44.9	≥45
	40-49	≤16.9	17-24.9	25-34.9	35-41.9	≥42
	50-59	≤14.9	15-21.9	22-39.9	34-39.9	≥40
	60-69	≤12.9	13-20.9	21-32.9	33-36.9	≥37

The self-testing method is different from the indirect testing method as the equation is varies with the test used. However, the final estimation value of VO_2MAX is compared to a standard table to rate the fitness of the subject's cardiovascular. The reference table is shown in Table 5. For an instance, if a female patient of age 35 having 29.1 $ml/kg/min$ of VO_2MAX, therefore she has a very poor cardiac fitness.

Table 5
Cardiovascular Fitness Rating [16]

Age / Class	Men				
	18-29	30-39	40-49	50-59	60-69
V.Poor	≤38.1	≤36.7	≤34.6	≤31.1	≤27.4
Poor	38.1-42.1	36.7-40.9	34.6-38.3	31.1-35.1	27.4-31.3
Fair	42.2-45.6	41.0-44.3	38.4-42.3	35.2-38.2	31.4-34.9
Good	45.7-51.0	44.4-48.8	42.4-46.7	38.3-43.3	35.0-39.4
Great	51.1-56.1	48.9-54.2	46.8-52.8	43.3-49.6	39.5-46.0
Superb	≥56.1	≥54.2	≥52.8	≥49.6	≥46.0

Age / Class	Women				
	18-29	30-39	40-49	50-59	60-69
V.Poor	≤31.6	≤29.9	≤28.0	≤25.5	≤23.7
Poor	31.6-35.4	29.9-33.7	28.0-31.5	25.5-28.6	23.7-26.5
Fair	35.5-39.4	33.8-36.7	31.6-35.0	28.7-31.3	26.6-29.0
Good	39.5-43.9	36.8-40.9	35.1-38.8	31.4-35.1	29.1-32.2
Great	44.0-50.1	41.0-46.8	38.9-45.1	35.2-39.8	32.3-36.8
Superb	≥50.1	≥46.8	≥45.1	≥39.8	≥36.8

IV. DISCUSSION

The direct testing method might provide the most accurate value of VO_{2MAX}. However, the method requires the use of very expensive equipment and professionals are needed along the whole test process either to handle the equipment or to monitor the test [5, 6, 17]. Besides, it requires the patient to go through a long waiting process as the facilities might be limited for selected hospital and this problem will eventually consume a lot of time and cause a spike in term of cost [17]. Clearly, low income patient will refuse to get treated because it is unaffordable, and it might also tighten the daily budget for the middle income patient. Therefore, alternative options such as indirect testing and self-testing method is provided.

On the other hand, indirect testing methods provide a more economic option where less expensive equipment is used. The protocol provides a set of a clear instruction and the process involved is organized. This can be seen on the procedure lay out by the Bruce Protocol. In terms of its ability to detect the cardiac abnormalities, it is more efficient as the whole process requires the patient to be attached to an ECG monitor along the test. The Modified Bruce Protocol is recommended for patients with immediate post myocardial infraction and it is also suitable for elderly patient [2]. The indirect method also takes the testing procedure suitable for the less fit and elderly patient into consideration [1]. That is the reason for the Naughton procedure to be introduced. However, the indirect testing gets tricky on its procedure which needs specialized personnel to monitor the test upon completion and also the use of ergometer in a laboratory or room to perform the test. Even though the method is less expensive, it is still costly due to the hire of professionals, limited hospital with such equipment and it is still a time consuming as the test can be easily eliminated if the procedure is not executed properly.

The problem with indirect testing method is overcome with the self-testing method. The self-testing method does not need any professional personnel for monitoring as the test only required subject to run or walk anywhere [10].

Subjects just need to follow simple instructions and even though the subject might not know how to use the equation, the subject may collect the needed data and present the data to the doctor for interpretation. The self-conducted test is suitable for everyone because it is much cheaper and easier to be implemented. However, some clarifications need to be made regarding The Rockport Fitness Walking Test (TRFWT) and Cooper Test. There are two equations used in TRFWT which is called the Kline Equation [18] and Dolgener Equation [19]. The Dolgener equation is shown as below:

$$VO_{2max}(ml/kg/min) = 94.6440 - (0.0819*BM) - (0.3232*A) + (8.4073*G) - (1.6157*T) - (0.1146*HR) \quad (5)$$

where: BM = Body mass (kilograms)
 A = Age
 G = Gender (F = 0, M = 1)
 T = Time complete (minute)
 HR = Heart rate

The equation used to finalize the estimation value of VO_{2MAX} in the procedure of TRFWT on the previous section is Kline Equation. It is the original set of procedure and equation developed by physiologist and cardiologist from the Department of Exercise Science of University of Massachusetts at Arnherst which later developed into Rockport Walking Institute [10]. The Dolgener Equation is actually used for Modified Rockport Fitness Test where the procedure changing from walking as fast as possible to brisk walking as majority of subjects complain on the task to maintain fast speed walking for 1 mile distance. Besides, the modified version shortens the distance by ¼ miles only because it is known that heart beat will reach steady state after three minutes of walking [20,21,22]. There is no absolute rejection for Dolgener Equation to be used as the modified procedure is better than the original procedure and it does give accurate estimation of VO_{2MAX}. However, in terms of accuracy, the Kline Equation is preferable as it gives higher precision of 35 to 50 percent accuracy compared to Dolgener Equation which gives 30 percent of accuracy. The higher accuracy n Kline Equation is due to the longer duration and distance on its testing procedure [22]. The clarification for the Cooper Test does not as complicated as TRFWT. Equation (4) is the original equation and a new equation as shown in Equation (6) is preferable as it achieves higher accuracy [13]. However, the estimations computed using Equation (4) and (6) only gives a slight different.

$$VO_{2MAX} \ (mL/kg/min) = 22.351 \ x \ D \quad (6)$$

where: D = Distance covered in kilometer

The disadvantage of the Cooper Test is that it is better to be applied on a fit individual because 12 minutes of continuous running is unsuitable for unfit and elderly individual. Meanwhile, the Heart Rate Ratio method can provide a good estimation as the heart rate is taken at high stress points of the heart for HR_{max} and at very relaxing pace for HR_{rest}. However, it is also better to be used by trained individual as the initial heart rate during the

procedure of collecting HR_{max} is quite difficult to be obtained for an untrained individual. Besides, it can be costly because of the use of treadmill as part of the procedure.

V. CONCLUSION

As a conclusion, the cardiac stress test offers a lot of options to measure the maximal oxygen uptake; VO_{2MAX}. The test can be direct method, indirect method which consists of the Bruce Protocol, Modified Bruce Protocol and Naughton Protocol or self-testing method which constitutes of TRFWT, Cooper Test and Heart Rate Ratio Method. It is proven that direct testing can provide the exact value of VO_{2MAX} and both indirect testing and self-testing methods can only provide the estimated value yet it is acceptable for early detection. These methods differ by its procedure, equipment and cost, but the purpose of these methods is the same, which is for cardiac abnormalities detection. Undergo the test will be helpful for early detection of heart problem, evaluation and analysis of the patient's heart condition which then lead to suggestion of best medication and alternative method to cure the patient and most importantly to help the patient to get treated regardless of the problem of reaching out for the treatment.

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