Pressure-Rate-Product Conducted Exercise Stress Testing
—A new protocol for exercise stress testing—

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The classical and standardized method for exercise stress testing is to increase a work load of a bicycle ergometer or treadmill by stepwise increase method. This procedure sometimes provokes a non-stepwise increase in the myocardial oxygen consumption. We, therefore, have developed a new exercise stress testing method for subjects with myocardial ischaemia. The work loads of the ergometer in continuously adjusted so that a linear increase in the PRP (systolic blood pressure x heart rate) could be obtained. Using this method, three subjects performed exercise stress testing. The results produced good linearities between the predicted PRP and actual PRP. It is suspected that this new method might be safe and applicable to patients with ischaemic heart disease.

Key words: Computer, Exercise, Ergometer, Pressure-Rate-Product.

INTRODUCTION

Exercise stress testing is a powerful tool in the diagnosis of patients with ischaemic heart disease (Rosing 1974, McNeer 1977, Tonkon 1977, Zohman 1977, Morris 1978, Berman 1978, Hollenberg 1980.) and in disclosing an occult arrhythmia (Lamb 1962, McHenry 1972, Gooch 1972, Anderson, 1972, Goldschlager 1973, Blackburn 1973, Jelinek 1974, DeMaria 1974, Udall, 1977.). To load cardiorespiratory function to a maximal extent, large muscle groups should be engaged. For this reason, two step stairs, bicycles, or treadmills have been the most used laboratory tests (Bruce 1974, Sheffield 1976.). The testing procedures vary from one laboratory to another. These exercise protocols, however, are given by predetermined work loads. Responses to the exercise may differ between treadmill and bicycle exercise, and between the protocols of exercise (Hermansen 1969, Frohlicher 1974, Pollock 1976). And cardiac responses to the work load may also differ according the sex, the age, and the physical condition of the subjects. Also the sudden, vigorous exercise in normal men may represent subendocardial ischemia (Bernard 1973). It is suspected, therefore, that sudden strenuous exercise may be a risk for the patients with ischaemic heart disease. And a light exercise to a normal subject may be a strenuous to a subject with ischaemic heart disease. Arstila reported a pulse-conducted triangular exercise-ECG test (Arstila 1972.). The test differs fundamentally from all previously reported exercise tests in that it is the heart rate which is standardized from moment to moment during the working period. This is performed because the heart rate is one of the chief determinants of the myocardial oxygen consumption and non-stepwise increase of heart rate is the most important for the test safety and reliability. The pressure rate product, however, is an index which is best correlated with myocardial oxygen consumption (Gobel 1977).

We have developed a system to control the work load according to the pressure rate product during exercise (pressure-rate-product conducted exercise
System Description

Hardware (Fig. 1)
The hardware system is based upon an Apple II plus microcomputer with 48-bytes of random access memory. The peripherals to this systems were:

1. an Apple II disk drive
2. one Epson dot matrix printer
3. one Video monitor
4. one A/D converter with ten-key (Denken Engineering)
5. one D/A converter (Denken Engineering)
6. one electrocardiographic monitor (Avionics-2900B)
7. one Gas-analysers (Fukuda-Electrometabolar)
8. one Flow meter (Minato Irika)
9. one Bicycle ergometer with controller (Tatebe)

The heart rate and ST-T segment were monitored by the electrocardiographic monitor. BCD coded digital signals of the ST-T and the heart rates were sent to the A/D converter. The flow and analog values of tidal volume were monitored by the Flow meter. The analog values of the flow and the tidal volume were sent to the A/D converter. The blood pressure were measured by using the sphygmomanometer. And the data were sent to the A/D converter via the Ten-key. Those values were sent to the CPU. Pressure rate products were calculated. Regulation signals were sent to the bicycle ergometer via the D/A converter. The ergometer was a electromechanically braked. When the control voltage was sent to the ergometer, the work load was automatically determined and was indifferent to the rate of revolulton of the ergometer. When the exercise is finished, the several parameters are calculated, printed out to the printer, and stored on the floppy disk.

Software
The software for the development and operation of the system was the Apple BASIC. Some speed critical parts were written not in BASIC, but in the Apple (6502) Assembly language. The system operates under following subroutines after receiving commands from the keyboard.

1. CALIBRATE -1: calibration of the expir-
atory gas concentrations, from the electrometabolar (expiratory gas analyser) to the CPU via the A/D converter.

CALIBRATE -2-: calibration of the recti-order (pen recorder): send a calibration signal from the CPU to the pen recorder via the D/A converter.

(2) INPUT -1-: receives a data of target pressure rate product from the keyboard.

INPUT -2-: receives digital values of physiological parameters from the A/D converter.

INPUT -3-: receives clock time signals generated in the A/D converter.

(3) CALCULATE: calculation of the pressure rate product, and the other parameters, such as the oxygen consumption, oxygen pulse, minute ventilation, etc.. The calculation of the values for the regulation of the bicycle ergometer is performed by the following formula.

if the actual PRP is below the value of target PRP, then we use the following formula

\[ WL(\text{watt}) = \frac{t \cdot \text{PRP} - a \cdot \text{PRP} - 200}{400} \]  

(1) The work load of the bicycle ergometer are controlled by the output voltages from the D/A converter. The output voltages are also regulated by the digital values from the CPU.

To regulate the work load by the digital values of the CPU, the relationship between the work load and the digital values of the CPU are examined.

(2) The flow diagram of the PRP conducted bicycle exercise stress testing is shown in Fig. 2. After receiving the start signal from the keyboard, the operator inputs the data of target pressure-rate-product. Then, the sub-

![Figure 2. Flow diagram of PRP-conducted exercise stress test system.](image)

**Algorithm and system evaluation.**

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ject exercises on the ergometer. While performing exercise, the physiological parameters except the blood pressures are monitored continuously. The blood pressure is measured every 30 to 60 seconds. And every 10 seconds the correction values of the work load are calculated, then the control signal is sent to the bicycle ergometer.

(3) Three healthy male subjects were the volunteers for the study. The exercises were performed by the following protocol. The protocol begins at 10000 mmHg-bpm of the target PRP for three minutes, and increasing the stages by the 5000 mmHg-bpm increase of PRP. Each stage is 3-minutes in duration.

RESULTS

(1) The relationship between the work load of the ergometer and the control electric voltage or the digital values of the CPU is shown in Fig. 3. The following formula was obtained.

\[ F(x) = 11.75 - 0.0184X + 0.0042X^2 \] \( (3) \)

where the \( F(x) \) is work load (watt) of the bicycle ergometer, and the \( X \) is digital values. (The D/A converter operates under 8 bit signals, thus the digital values are between 0 to 255).

under the formula, by adding a numerical number of 1 to the present \( X \)-value, the work

![Figure 3. Relationship between work load of the bicycle ergometer and the binary output signals of the CPU.](image)

<table>
<thead>
<tr>
<th>Time (min.)</th>
<th>Target PRP (mmHg x bpm)</th>
<th>Actual PRP (mmHg x bpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Subject-1-</td>
</tr>
<tr>
<td>rest</td>
<td>12998</td>
<td>9896</td>
</tr>
<tr>
<td>rest</td>
<td>12544</td>
<td>9796</td>
</tr>
<tr>
<td>rest</td>
<td>12672</td>
<td>9672</td>
</tr>
<tr>
<td>exercise</td>
<td>1 10000</td>
<td>14300</td>
</tr>
<tr>
<td></td>
<td>2 10000</td>
<td>13390</td>
</tr>
<tr>
<td></td>
<td>3 10000</td>
<td>13780</td>
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<tr>
<td></td>
<td>4 15000</td>
<td>14872</td>
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<tr>
<td></td>
<td>5 15000</td>
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<td>6 15000</td>
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<td>7 20000</td>
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<td>8 20000</td>
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<td>9 20000</td>
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<td>10 25000</td>
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<td>14 30000</td>
<td>27280</td>
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<tr>
<td></td>
<td>15 30000</td>
<td>28888</td>
</tr>
</tbody>
</table>
loads increase 1 or 2 watts between the work loads of 83 and 217 watts.

(2) In the Table 1, the target PRP and actual PRP during exercise (exercise PRP) in three subjects are shown. At the initial stage, the differences between target PRP and exercise PRP is somewhat large. As the stage increased, the differences became smaller. When the resting PRP is above the initial target PRP as in the Subject -1-, the exercise PRP could not be lowered to the target PRP.

DISCUSSION

A computer system for automatic control of PRP during exercise has been developed. In this system, the work loads were altered according to the PRP (systolic blood pressure x heart rate) of the subject during exercise. In this paper, the exercise protocol was multistage and non-interrupted type. The difference between target-PRP and actual-PRP 15 minutes after the beginning of the exercise in three subjects were from -1112 to 1122 mmHg-bpm. It is suspected that the target PRP could be achieved by the system during exercise.

In controlling the work load by actual- or target-PRP, the work-load is increased if the actual-PRP is below the target-PRP, and increased if the actual-PRP is above the target-PRP by using the formulas shown above. The formulas to control the work load were tentatively determined.

In the software, the algorithm to treat a VPC, a fall in blood pressure, or fall in heart rates, which were serious parameter in exercise, were not included. Thus, if the hypotension develops during the exercise, the work load might increase theoretically. In that case, however, the exercise should be terminated (Irving 1977).

The heart rates were monitored continuously, but the blood pressures were measured intermittently and manually every 30 to 60 seconds, and the bicycle was controlled every 10 seconds in this system. There might be some delay in controlling the work load. In order to be more accurate, the blood pressures have to be measured by invasive method and the bicycle ergometer should be controlled by beat-to-beat method. But the invasive monitoring of the blood pressure is neither practical nor convenient.

The system presented here is similar to those of Arstila (Arstila 1972). These systems, however, had took the heart rate for controlling the workload. Because, they suspected that the correlation of the changes in the heart rate x systolic pressure index of myocardial oxygen consumption is much higher with changes in heart rate than with changes in systolic pressure.

The changes in heart rate and the changes in blood pressure is not always parallel, especially when some drugs are utilized. For instance some drug decreases the blood pressure, whereas increases heart rate. In examining the efficacy of the drug in patients with ischaemic heart disease, it would be the PRP to predict the myocardial oxygen consumption. Thus, the PRP conducted bicycle exercise testing might be better than that of the heart rate conducted bicycle exercise testing.

The methods and protocols which are appropriate for performing stress testing vary according to the nature of the information being sought by the testing. If the exercise is to be done in subjects with ischaemic heart disease, or when the aim of a test is to provoke myocardial ischaemia, a controlled and non-stepwise increase of the myocardial oxygen consumption is important for test safety and reliability. The PRP is a useful parameter to predict a myocardial oxygen consumption. Thus, the PRP controlled exercise stress testing might be a new protocol for subjects suffering from ischaemic heart disease.

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