Cardiac Output as a Function of Ventricular Rate in a Patient with Complete Heart Block

By Peter G. Gaal, M.D., Stanley J. Goldberg, M.D., and Leonard M. Linde, M.D.

The physician occasionally encounters a situation in clinical practice that offers unique opportunities to study physiologic principles relating to cardiac function that cannot be evaluated under ordinary circumstances. We recently studied a patient who had developed complete heart block without evidence of other cardiac or systemic disease. With heart rate controlled by an external pacemaker, the effects of rate, position, and exercise on cardiac output, systemic pressure, and stroke volume were assessed.

Benchimol et al. reported hemodynamic findings in a 45-year-old man with complete heart block associated with coronary artery disease. No significant changes in stroke index were found with exercise. Our results suggest that this may have been due to the existence of coronary artery disease and myocardial damage. The work of Miller et al. in dogs with induced chronic heart block lends support to the concept that stroke volume may alter appreciably in response to exercise with its increased demand on the heart.

Case Report

D.P., a 33-year-old married Caucasian woman, was entirely well until April 1960, when she suddenly developed complete heart block with a ventricular rate of 30 beats per minute and congestive heart failure. Cardiac catheterization revealed only mild pulmonary hypertension, high end-diastolic ventricular pressure, and mild tricuspid insufficiency. Subsequent extensive laboratory studies have revealed no evidence of general or intracardiac disease other than the heart block.

Medical management did not completely relieve the patient’s congestive heart failure, and isoproterenol increased the ventricular rate to only 48 beats per minute. A thoracotomy was performed, therefore, and bipolar electrodes were sutured into the ventricular myocardium and connected to an external pacemaker. Biopsy of the right atrial appendage showed moderate myocardial hypertrophy; pericardial biopsy revealed old, healed, nonspecific pericarditis. With heart rate fixed at 60 beats per minute, the patient was markedly improved. Two years later, it was necessary to replace the myocardial electrodes because of localized fibrosis.

With an internal pacemaker set at 68 beats per minute, the patient was able to perform all household tasks for her family of six and to participate in athletics without difficulty. She remained well until May 1963, when she suddenly developed a ventricular rate of 200 beats per minute. The electrocardiogram at this time revealed a pacemaker rate of 400 (fig. 1). An external pacemaker was connected to the implanted electrode leads to re-establish the normal rate. One week later, a series of cardiac function tests were performed, as recorded below. A new internal pacemaker was implanted with a rate of 75, which later stabilized at 68 beats per minute. The patient is again asymptomatic and leading a full normal life at home.

Method

Catheters were introduced into the right atrium and left subclavian artery by means of the Seldinger technic. Cardiac output was measured in duplicate with the indocyanine-green dye-dilution technic. Continuous radio-electrocardiographic tracings and direct intra-arterial pressures were recorded. Heart rate was set successively at 50, 60, 75, 90, and 110 beats per minute with an external pacemaker. Cardiac output and systemic pressure were measured at these various rates, with the patient in the supine position, sitting on a bicycle ergometer, and during exercise at a work load of 300 Kg. meters per minute. The pacemaker-heart rate was checked for accuracy by electrocardiographic monitoring. Cardiac output, cardiac index, stroke volume, stroke index, and systemic vascular resistance were calculated.

Three and one-half months after implantation of an internal pacemaker, the patient was re-
studied with the same technic, but at the fixed pacemaker rate.

**Results**

Cardiac index as a function of rate, position, and activity is shown graphically in figure 2. With the patient in the supine position, the cardiac index increased progressively to about 3 liters per minute at a rate of 75 beats. No further increase in cardiac index was found at higher rates. The slight decrease occurring at a rate of 90 was probably artifact. With the patient sitting on a bicycle ergometer, the cardiac index increased steadily from an initial level of 1.91 liters per minute at a rate of 50 to a maximum of 2.52 liters per minute at a rate of 90. During exercise, the cardiac index rose to 3.34 liters per minute at a heart rate of 75, and did not increase significantly when the rate was raised above this level.

Stroke volume increased to a maximum at a heart rate of 75, both in the recumbent position and during exercise, and declined at higher rates (fig. 3). With the patient in the sitting position, a progressive decrease in stroke volume occurred as heart rate was increased from 50 to 90 beats per minute.

Mean arterial pressure was higher in the sitting position than in the recumbent state,

**Figure 1**

*Electrocardiograms taken (upper) prior to insertion of internal pacemaker, (middle) at time of failure of pacemaker (lower) after implanting new unit. AR, atrial rate; VR, ventricular rate.*

**Figure 2**

*Cardiac index as a function of rate, position, and activity.*
Response of stroke volume to rate, position, and activity.

and increased progressively during exercise with each increment in heart rate (table 1).

During the second study, with heart rate fixed at 68 beats per minute, cardiac output and stroke volume again fell as the patient changed from a recumbent to a sitting position. Exercise at a work load of 300 Kg. meters per minute again elicited an increase in cardiac output and stroke volume (table 2).

Discussion

Increased oxygen needs during exercise are normally satisfied by an increase in cardiac output and arterial-venous oxygen difference. Rushmer and others have demonstrated that although heart rate and arterial-venous oxygen difference progressively increase with exercise in the normal human subject, stroke volume need not change. Conversely, in trained athletes or in patients with chronic volume loads on the heart, cardiac output may increase by an increase in stroke volume although there is relatively little change in heart rate.

The patient studied by Benchimol and his associates was a 45-year-old diabetic who had had known coronary heart disease for several years preceding the development of heart block. It is significant that artificially increasing his cardiac rate from its resting level of 35 beats per minute resulted in an increase in cardiac output, left ventricular work, and systemic pressure. Stroke volume, however, remained unchanged throughout all cardiac rates. In a second part of the study, after a pacemaker with a fixed cardiac rate of 72 beats per minute had been implanted, moderate exercise produced no change in cardiac output or stroke volume. These investigators mention the possibility that failure to increase stroke volume may indicate the presence of significant myocardial damage. In our studies on a young healthy woman with idiopathic heart block, cardiac

Table 1

Initial Studies Made with External Pacemaker Set at Varying Rates

<table>
<thead>
<tr>
<th>Position</th>
<th>Heart rate</th>
<th>Cardiac output</th>
<th>Cardiac index</th>
<th>Stroke volume</th>
<th>Stroke index</th>
<th>Arterial pressure</th>
<th>Mean arterial pressure</th>
<th>Systemic vascular resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recumbent</td>
<td>50</td>
<td>2.95</td>
<td>1.84</td>
<td>59</td>
<td>37</td>
<td>100/48</td>
<td>76</td>
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<tr>
<td></td>
<td>60</td>
<td>3.60</td>
<td>2.25</td>
<td>60</td>
<td>38</td>
<td>95/56</td>
<td>70</td>
<td>19.4</td>
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<tr>
<td></td>
<td>75</td>
<td>4.70</td>
<td>2.94</td>
<td>61</td>
<td>38</td>
<td>109/60</td>
<td>73</td>
<td>15.6</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>4.09</td>
<td>2.56</td>
<td>45</td>
<td>28</td>
<td>99/59</td>
<td>70</td>
<td>17.1</td>
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<tr>
<td></td>
<td>110</td>
<td>4.76</td>
<td>2.97</td>
<td>43</td>
<td>27</td>
<td>106/75</td>
<td>78</td>
<td>16.4</td>
</tr>
<tr>
<td>Sitting</td>
<td>50</td>
<td>3.06</td>
<td>1.91</td>
<td>61</td>
<td>38</td>
<td>140/90</td>
<td>110</td>
<td>35.9</td>
</tr>
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<td></td>
<td>60</td>
<td>3.32</td>
<td>2.07</td>
<td>55</td>
<td>34</td>
<td>144/90</td>
<td>110</td>
<td>30.8</td>
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<td></td>
<td>75</td>
<td>3.49</td>
<td>2.18</td>
<td>47</td>
<td>29</td>
<td>150/92</td>
<td>110</td>
<td>20.9</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>4.03</td>
<td>2.52</td>
<td>45</td>
<td>28</td>
<td>130/94</td>
<td>110</td>
<td>27.3</td>
</tr>
<tr>
<td>Exercise (sitting)</td>
<td>60</td>
<td>3.57</td>
<td>2.23</td>
<td>60</td>
<td>38</td>
<td>138/80</td>
<td>110</td>
<td>30.8</td>
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<td></td>
<td>75</td>
<td>5.26</td>
<td>3.28</td>
<td>70</td>
<td>44</td>
<td>160/100</td>
<td>130</td>
<td>24.7</td>
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<tr>
<td></td>
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<td>3.34</td>
<td>59</td>
<td>37</td>
<td>158/112</td>
<td>123</td>
<td>23.0</td>
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</table>

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output increased with increasing heart rates up to 75 beats per minute. No further increase occurred at faster rates. During exercise, optimal cardiac output was also achieved at 75 beats per minute, with little change at a rate of 90.

The unique finding in the present study was the change in stroke volume. With the patient in the sitting position, stroke volume progressively decreased with increasing heart rate. The recumbent position facilitated greater venous return and, secondarily, greater cardiac output. Optimal stroke volume was reached at a rate of 75 beats per minute. With light exercise, stroke volume increased significantly when the heart rate was increased from 60 to 75, but decreased with higher rates (fig. 4).

These findings indicate that our patient is able to increase stroke volume significantly as the result of increased exercise demands. She resembles the trained athlete who has acquired the ability to increase cardiac output by increasing stroke volume. In contrast, the patient with myocardial disease may not be able to increase stroke volume, and must rely on changes in heart rate.

The re-evaluation of cardiovascular hemodynamics following implantation of an internal pacemaker revealed similar responses to change in position and activity. As anticipated, a change from the recumbent to the sitting position was associated with decreased venous return from the lower extremities and a concomitant decrease in cardiac output and stroke volume. Exercise resulted in a 43-per cent increase in stroke volume and cardiac output. Since cardiac rate remained fixed, the increase in output must be attributed entirely to an increase in stroke volume.

An additional finding was that a heart rate of 75 beats per minute was optimal for this patient. Cardiac output increased no further, either with exercise or in the sitting or recumbent positions, at heart rates above this level. At the same time, stroke volumes were at their maximum.

Coronary artery disease with myocardial ischemia has long been considered the main etiologic factor in acquired complete heart block. Recent evidence suggests that myocarditis and fibrosis may also be responsible for a significant number of permanent blocks. The etiologic basis of our patient's heart block remains unknown. However, localized myocarditis with secondary fibrosis is a likely possibility. If this is the case, all evidence of

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<tr>
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<th>Cardiac index</th>
<th>Stroke volume</th>
<th>Stroke index</th>
<th>Arterial pressure</th>
<th>Mean arterial pressure</th>
<th>Systemic vascular resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recumbent</td>
<td>68</td>
<td>4.35</td>
<td>2.72</td>
<td>64</td>
<td>40</td>
<td>117/72</td>
<td>92</td>
<td>21.1</td>
</tr>
<tr>
<td></td>
<td>68</td>
<td>4.35</td>
<td>2.72</td>
<td>64</td>
<td>40</td>
<td>124/80</td>
<td>94</td>
<td>21.7</td>
</tr>
<tr>
<td>Sitting</td>
<td>68</td>
<td>3.30</td>
<td>2.06</td>
<td>49</td>
<td>31</td>
<td>120/78</td>
<td>90</td>
<td>27.4</td>
</tr>
<tr>
<td>Exercise</td>
<td>68</td>
<td>4.54</td>
<td>2.84</td>
<td>67</td>
<td>42</td>
<td>160/82</td>
<td>103</td>
<td>22.7</td>
</tr>
<tr>
<td>(sitting)</td>
<td>68</td>
<td>4.94</td>
<td>3.09</td>
<td>73</td>
<td>46</td>
<td>140/80</td>
<td>96</td>
<td>19.5</td>
</tr>
</tbody>
</table>

Figure 4

Changes in cardiac output and stroke volume associated with position and activity.

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myocardial inflammation or other cardiac difficulties has subsided and, except for the persistent block, our patient is in excellent health.

Summary

Hemodynamic effects of varying heart rate and activity have been studied in a young woman in good health except for complete heart block. As cardiac rate was increased from 50 to 110 beats per minute by means of an external cardiac pacemaker, cardiac output and stroke volume were found to reach maximum values at a rate of 75. Stroke volume increased 43 per cent with exercise when heart rate was fixed at 68 beats per minute. The ability of this patient to increase stroke volume with exercise, in contrast to average normal subjects, may be related to her past experience with chronically increased volume loads on the heart secondary to heart block.

References


Epilepsy from Palpitation of the Heart.—Mrs. C., aged between 40 and 50, who had been for many years subject to coughs with violent spitting of blood, and copious expectoration, attended with a quick and full pulse, all of which were often relieved but never wholly cured, was also often attacked with fits of palpitation of the heart. In the month of October 1809, her cough being better than usual, she had for many days more or less of the palpitation, accompanied with a sense of fulness and throbbing pain in her head. One day, while she was in an upholsterer's shop looking at new mahogany furniture, the smell of the oil, which was very disagreeable to her, produced a great increase of palpitation, which was soon followed by convulsions, foaming at the mouth, and all the other symptoms of epilepsy. She was soon relieved by blood-letting, Citrate of Potash in the state of effervescence with Squill, and purgatives.

On the 15th of November following, she experienced for two days a threatening of the epileptic symptoms. A violent degree of palpitation of the heart produced a throbbing pain and confusion in the head, accompanied with loss of memory.

The symptoms were relieved in the manner before related; and to this day, June 1813, the patient has suffered no relapse of the disease.—Collections from the Unpublished Medical Writings of the Late Caleb Hillier Parry, M.D.F.R.S. Vol. I., London, Underwoods, Fleet-Street, 1825, p. 415.
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