Impact of Dual-Chamber Permanent Pacing in Patients With Obstructive Hypertrophic Cardiomyopathy With Symptoms Refractory to Verapamil and β-Adrenergic Blocker Therapy

Lameh Fananapazir, MRCP, MD; Richard O. Cannon III, MD, FACC; Dorothy Tripodi, RN; and Julio A. Panza, MD

**Background.** Patients with obstructive hypertrophic cardiomyopathy (HCM) with symptoms refractory to drugs (β-blockers or verapamil) are candidates for cardiac surgery (left ventricular septal myectomy or mitral valve replacement). The present study examines prospectively the ability of dual-chamber (DDD) pacing to improve symptoms and relieve left ventricular outflow obstruction in such patients.

**Methods and Results.** Forty-four consecutive patients with obstructive HCM who had failed to benefit from pharmacotherapy underwent treadmill exercise tests, echocardiography, and cardiac catheterization before and 1.5–3 months after implantation of a DDD pacemaker. Symptoms (angina, dyspnea, palpitations, presyncope, and syncope), New York Heart Association functional class status (1.7±0.7 versus 3.4±0.5, \( p<0.00001 \)), and exercise durations were improved at follow-up evaluation. This was associated with significant reduction in left ventricular outflow tract gradient (38±38 versus 87±43 mm Hg, \( p<0.0001 \)) and significant increases in cardiac output and systemic arterial pressures. Notably, when pacing was discontinued and comparisons were made in sinus rhythm, treadmill exercise durations were greater and left ventricular outflow tract gradients were less at the follow-up evaluation compared with the baseline study.

**Conclusions.** DDD pacing is an effective alternative to surgery in most patients with obstructive HCM with drug-refractory symptoms. The beneficial effects of pacing continue to be evident when pacing is acutely discontinued. *(Circulation 1992;85:2149–2161)*

**Key Words** • dual-chamber pacing • obstructive hypertrophic cardiomyopathy

Approximately 25% of patients with hypertrophic cardiomyopathy (HCM) have substantial obstruction to left ventricular outflow,\(^1\) which constitutes an important determinant of clinical course.\(^1–9\) Thus, patients with obstructive HCM frequently have severe symptoms—chest pain, dyspnea, presyncope or frank syncope, and palpitations. Although these symptoms may initially respond to therapy with β-adrenergic blockers\(^10–12\) or verapamil,\(^13–15\) eventually, many patients become refractory or develop side effects to these medications.\(^9,16–25\) A therapeutic approach that has been adopted by a number of institutes including our own over the past 25 years in patients with obstructive HCM who fail to benefit from pharmacotherapy has been to relieve the left ventricular outflow tract (LVOT) pressure gradient by left ventricular septal myectomy or by mitral valve replacement.\(^25–38\) Frequently, septal myectomy fails to relieve left ventricular outflow obstruction, and both operations are associated with significant mortality and morbidity\(^27\); therefore, a need still exists for alternative therapeutic strategies in patients with obstructive HCM.

The LVOT obstruction in obstructive HCM is dynamic and not fixed. A primary systolic event is the occurrence of anterior movement of the mitral valve leaflet (SAM) toward the interventricular septum. This is believed to occur as a result of forces generated by blood ejected at high velocities through the narrowed LVOT.\(^1–9\) Marked SAM and prolonged mitral-septal apposition are always associated with substantial LVOT pressure gradients and frequently with mitral regurgitation.\(^1–9\)

It has been suggested that dual-chamber pacing (DDD) reduces LVOT pressure gradients and improves symptoms in patients with obstructive HCM.\(^39–46\) This approach is based on the concept that preexcitation of the interventricular septum by atrial synchronized right ventricular pacing or atroventricular (AV) sequential pacing would cause the septum to move away from the left ventricular wall during systole, resulting in an increase in LVOT dimensions and hence reduction in LVOT blood velocities. This would in turn diminish SAM, resulting in further relief of the LVOT obstruction and less severe mitral regurgitation. Others, however, have reported that this technique is not of thera-
TABLE 1. Clinical Characteristics of the 44 Consecutive Patients With Hypertrophic Obstructive Cardiomyopathy Who Were Treated With Dual-Chamber Pacemakers

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Number (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>22 (50%)</td>
</tr>
<tr>
<td>Age (years)</td>
<td>49±14</td>
</tr>
<tr>
<td>Range</td>
<td>17–71</td>
</tr>
<tr>
<td>Prior cardiac surgery for LVOT obstruction</td>
<td>5 (11%)</td>
</tr>
<tr>
<td>Symptomatic presentation</td>
<td></td>
</tr>
<tr>
<td>Chest pain</td>
<td>32 (73%)</td>
</tr>
<tr>
<td>Dyspnea</td>
<td>44 (100%)</td>
</tr>
<tr>
<td>Orthopnea</td>
<td>18 (41%)</td>
</tr>
<tr>
<td>Paroxysmal nocturnal dyspnea</td>
<td>19 (43%)</td>
</tr>
<tr>
<td>Palpitations</td>
<td>27 (61%)</td>
</tr>
<tr>
<td>Presyncope</td>
<td>33 (75%)</td>
</tr>
<tr>
<td>Syncope</td>
<td>23 (52%)</td>
</tr>
<tr>
<td>NYHA functional class</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>29 (66%)</td>
</tr>
<tr>
<td>IV</td>
<td>15 (34%)</td>
</tr>
<tr>
<td>Echocardiographic characteristics</td>
<td></td>
</tr>
<tr>
<td>Anterior ventricular septum (mm)</td>
<td>24.9±5.6</td>
</tr>
<tr>
<td>Posterior ventricular septum (mm)</td>
<td>19.3±3.9</td>
</tr>
<tr>
<td>Anterolateral LV free wall (mm)</td>
<td>17.9±4.1</td>
</tr>
<tr>
<td>Posterior LV free wall (mm)</td>
<td>13.0±4.8</td>
</tr>
<tr>
<td>Left ventricular diastolic dimension (mm)</td>
<td>40.7±5.9</td>
</tr>
<tr>
<td>Left ventricular systolic dimension (mm)</td>
<td>26.0±5.0</td>
</tr>
<tr>
<td>Left atrial dimension (mm)</td>
<td>47.4±7.1</td>
</tr>
<tr>
<td>Aortic root (mm)</td>
<td>30.8±3.1</td>
</tr>
<tr>
<td>Severity of SAM (0–4+)</td>
<td>3.6±0.8</td>
</tr>
<tr>
<td>CW peak LVOT velocity (m/sec)</td>
<td>4.0±1.3</td>
</tr>
<tr>
<td>Estimated LVOT gradient (mm Hg)</td>
<td>64±7</td>
</tr>
</tbody>
</table>

LVOT, left ventricular outflow tract; NYHA, New York Heart Association; LV, left ventricular; SAM, systolic anterior movement of the mitral valve; CW, continuous-wave Doppler.

The present investigation was to evaluate prospectively the efficacy of DDD pacing in a consecutive group of severely symptomatic patients with obstructive HCM who had failed to benefit from pharmacotherapy and were therefore candidates for operative relief of the LVOT obstruction.

Methods

Patient Population

The study consisted of 44 consecutive patients with obstructive HCM (Table 1) in whom the therapeutic efficacy of DDD pacing to relieve severe symptoms was evaluated between May 1990 and October 1991. During this study period, all patients who were candidates for operative relief of LVOT obstruction elected to enter the study. Patients were in New York Heart Association (NYHA) functional class III or IV and had failed to benefit from verapamil (240–480 mg/day) and β-adrenergic blockers (propranolol 240–360 mg/day or atenolol 100 mg/day). In addition, disopyramide (600 mg/day) had failed to improve symptoms in four patients. Informed consent was obtained in accordance with a study protocol approved by the Institute Review Board of the National Heart, Lung, and Blood Institute. In each patient, the diagnosis of HCM was made by the echocardiographic demonstration of a nondilated hypertrophied left ventricle in the absence of another cardiac or systemic cause for the left ventricular hypertrophy.47

Criteria for entry into the study were 1) presence of severe cardiac symptoms refractory to pharmacotherapy; 2) presence of significant obstruction (LVOT gradient ≥30 mm Hg at rest or >50 mm Hg after provocation maneuvers, that is, Valsalva, amyl nitrite inhalation, or isoproterenol infusion); and 3) absence of atrial arrhythmias. All cardiovascular drugs were discontinued more than five half-lives before study. Studies before implantation of pacemaker included 12-lead electrocardiogram, echocardiogram, treadmill exercise tests, cardiac catheterization, and left ventricular and coronary angiography. None of the patients had coronary artery disease. All patients had undergone 48-hour Holter monitoring before this study and did not have bradyarrhythmia or tachyarrhythmia. The patients were discharged from the hospital 3–5 days after receiving a DDD pacing device (with no medication) and were reevaluated after 1.5 months (first 24 patients) or 3 months (the remaining 20 patients) of chronic DDD pacing. At the follow-up admission, the following studies were repeated: 12-lead electrocardiogram, echocardiogram, treadmill exercise tests, and cardiac catheterization.

Pulse Generators and Programmed Parameters

Two models of pulse generators were implanted (selected by random order): the Pacesetter 2022T (Syncrony, n=21) and the Medtronic 7070 (Synergist II, n=23). As all patients had chronotropic competence, the pulse generators were programmed to DDD mode (sensor programmed to PASSIVE) with lower and upper heart rates of 70 and 165 beats per minute, respectively. In all patients with the Pacesetter 2022T model, the AV delay was programmed to the lowest value (125 msec), and the rate-adaptive AV interval shortening was activated. The AV delay in patients with the Medtronic 7070 was 125 msec in 11 patients, 100 msec in seven patients, and 75 msec in five patients. These were the longest AV delays that allowed for maximal preexcitation (widest-paced QRS duration).

Treadmill Exercise Tests

Exercise tests were performed during sinus rhythm at the baseline study and during sinus rhythm and DDD pacing at the follow-up study on a motor-driven treadmill using standard Bruce protocol.48 The methods used to compare exercise tests at the follow-up evaluation were similar to those described previously.49 Briefly, the tests were supervised by two individuals. One was responsible for the selection of the pacing mode used first (randomized) and for continuous electrocardiographic recording. The second person supervised the patient during exercise and encouraged the patient to his/her (symptom-limited) maximum effort. Neither this physician nor the patient was aware of the pacing mode. The arterial pressure was recorded continuously using an indwelling brachial catheter. The following were measured: 1) exercise duration; 2) heart rate and arte-
**FIGURE 1.** Bar graphs show prevalence and severity of individual cardiac symptoms before and after dual-chamber pacing in 44 patients with obstructive hypertrophic cardiomyopathy. –, Symptoms absent; +, mild symptoms; ++, moderate symptoms; ++++, severe symptoms.

**FIGURE 2.** Diagram of changes in New York Heart Association functional class status (NYHA-FC) in 44 patients with obstructive hypertrophic cardiomyopathy after 1.5–3 months of dual-chamber pacing.
tion was modified to obtain the maximum velocity signal from the LVOT. Particular care was taken to separate the LVOT signals from that of mitral regurgitation. Orientation of the Doppler beam was assumed to be virtually parallel to the direction of the systolic flow (i.e., angle of incidence <20°), and, therefore, no routine angle correction was incorporated in the calculation of LVOT gradient from the continuous-wave Doppler waveform. LVOT pressure gradient was estimated using the modified Bernoulli equation:

\[ G = 4V^2, \]

where \( G \) = LVOT gradient (mm Hg) and \( V \) = maximum LVOT velocity (m/sec).

LVOT obstruction was also assessed from M-mode echocardiogram by analysis of the presence and severity of SAM and graded as follows: 0, absent; 1+, present with minimum distance between mitral valve and ventricular septum during systole >10 mm; 2+, without mitral-septal contact but with a distance <10 mm between the mitral valve and septum; 3+, brief mitral-septal contact (<30% of echocardiographic systole); 4+, prolonged apposition of mitral valve leaflet with septum (>30% of echocardiographic systole).

**Cardiac Catheterization**

Right heart pressures and cardiac output were measured with a thermodilution Swan-Ganz catheter. The LVOT gradient was recorded using the side arm of a Cordis 8F sheath and a 7F Cordis end-hole catheter placed in the left ventricle. In all patients, the right femoral and ascending aortic pressures were compared and agreed within 5 mm Hg. During cardiac catheterization, a 5F quadripolar catheter was advanced via the left femoral vein to the right ventricular apex, and another 5F quadripolar catheter was placed in the right atrial appendage. At the baseline study, after measurement of right and left heart pressures and cardiac outputs during normal sinus rhythm, the hemodynamic indexes were remeasured during right atrial (RA) and AV sequential (AV delay of 120 msec) pacing modes at heart rates of 100, 120, and 150 beats per minute. At the follow-up study, the hemodynamic indexes were recorded during sinus rhythm and DDD pacing, and in addition, during RA and AV sequential pacing modes at heart rates of 100 and 120 beats per minute by external programming of the pacemaker device. At each heart rate, the selection of the initial pacing mode was randomized.

**Statistics**

Data are expressed as mean±1 SD. Only paired data were compared using Wilcoxon's sign rank tests. Contingency tables were evaluated by \( \chi^2 \) and Fisher's exact tests. A value of \( p<0.05 \) was considered significant. The baseline and follow-up clinical and hemodynamic findings in patients who were evaluated after 1.5 months of DDD pacing were not significantly different compared with patients studied after 3 months of pacing. Thus, the findings in the 44 patients were analyzed as a single group.

**Results**

**Changes in Symptomatic Status**

The impact of DDD pacing on symptoms is shown in Figure 1. None of the patients reported worsening of their symptoms. The frequency and severity of the following symptoms were significantly reduced: effort-induced dyspnea, orthopnea, paroxysmal nocturnal dyspnea, chest discomfort, palpitations, and presyncope (Figure 1). DDD pacing also appeared to prevent syncope: 15 patients had a history of effort- or postural-induced syncope that occurred with a frequency ≥1/month (one patient had more than one episode of syncope per week). During a follow-up period of 9±3 months (maximum 13 months), only one of the 15 patients had a further episode of syncope.

The NYHA functional status of the patients improved by one class in 12 patients (27%) and by two or more classes in 30 patients (68%) (Figure 2). The mean NYHA functional class status decreased from 3.4±0.5 to 1.7±0.7, \( p<0.0001 \). Although most patients were improved, six patients (14%) remained in functional class III. One of two patients who did not derive symptomatic benefit from DDD pacing has subsequently undergone left ventricular septal myectomy.

**Treadmill Exercise Performance**

Treadmill exercise durations achieved during DDD pacing mode at the follow-up study were significantly greater than those achieved during sinus rhythm before pacemaker implantation: 8.8±3.3 versus 6.3±2.3 min-
utes, \( p < 0.0001 \). The exercise durations during DDD pacing were also significantly greater than those achieved during sinus rhythm at the follow-up study: 8.8±3.3 versus 7.8±3.3 minutes, \( p < 0.02 \) (see Figure 3). Notably, exercise durations during normal sinus rhythm at the follow-up study were significantly increased compared with the baseline study: 7.8±3.3 versus 6.3±2.3 minutes, \( p < 0.001 \) (Figure 3).

The mean exercise peak heart rate at the baseline study (sinus rhythm) was 154±19 beats per minute, and at the follow-up evaluation, the mean exercise peak heart rates during sinus rhythm and DDD pacing were 159±18 and 158±19 beats per minute, respectively. Heart rate and arterial blood pressures responses to exercise during DDD pacing were not significantly different compared with exercise tests performed in sinus rhythm at the baseline and at the follow-up studies. All patients exceeded a respiratory quotient of 1.0. At the follow-up evaluation, oxygen consumption rates at peak exercise during DDD pacing were significantly higher than peak oxygen consumption rates during sinus rhythm: 20.4±2.3 versus 18.5±2.4 ml \( \text{O}_2/ \text{min/kg} \), \( p < 0.005 \).

**Echocardiographic Evaluation of LVOT Obstruction**

Although all patients underwent echocardiography, data for all three studies (normal sinus at baseline,
normal sinus rhythm, and DDD pacing at follow-up) were available in 23 patients. Indexes of LVOT obstruction (severity of SAM and Doppler LVOT velocities) were reduced significantly during DDD pacing mode compared with those recorded during normal sinus rhythm at both the baseline study and at the follow-up examination (Figure 4 and Table 2). Notably, with discontinuation of pacing at the follow-up study, the LVOT Doppler velocities in normal sinus rhythm were also significantly less than those recorded at the baseline study (Table 2).

Hemodynamic Evaluation

Acute changes in pacing mode and heart rate had significant and independent effects on the hemodynamic indexes at the two cardiac catheterization studies. Unexpectedly, however, after chronic DDD pacing, the hemodynamic indexes at the follow-up evaluation recorded during normal sinus rhythm were noted to have significantly improved compared with the hemodynamic findings noted during sinus rhythm at the baseline study.

Baseline Cardiac Catheterization

Hemodynamic changes caused by AV sequential pacing. The pulmonary arterial (PA) and pulmonary arterial capillary wedge (PCW) pressures during RA and AV sequential pacing modes were similar. However, the hemodynamic responses to increases in heart rate during the two pacing modes differed significantly in the following respects: LVOT gradients and left ventricular systolic pressures were lower and systemic arterial pressures were higher during AV sequential pacing mode (Figures 5 and 6). Cardiac outputs were significantly higher during AV sequential pacing compared with RA pacing at heart rates of 120 and 150 beats per minute (Figure 5). During AV sequential pacing, cardiac outputs were higher than sinus rhythm when heart rate was increased to 100 and 120 beats per minute, but cardiac
output fell when heart rate was further increased to 150 beats per minute (Figure 5). However, cardiac output during RA pacing was higher than sinus rhythm only at a heart rate of 100 beats per minute and fell dramatically at a heart rate of 150 beats per minute. Thus, whereas during AV sequential pacing at 150 beats per minute, cardiac output was reduced by only 0.3 l/min compared with cardiac output measured in sinus rhythm (79±17 beats per minute), it fell by 1.1 l/min during RA pacing at 150 beats per minute (Figure 5). Indeed, the reductions in LVOT gradient and left ventricular systolic pressures during RA pacing were attributable to the deleterious effects of rapid heart rates on cardiac output.

Rate-dependent changes in hemodynamic indexes. Increases in heart rate during both RA and AV sequential pacing modes were associated with significant increases in PA, PCW, and systemic arterial pressures (Figure 5). These findings were accompanied by significant reductions in left ventricular systolic pressure and LVOT gradients (Figure 5).

Follow-up Cardiac Catheterization

Hemodynamic changes caused by changes in heart rate and pacing mode. Similar to the findings at the baseline study, the PA and PCW pressures at the follow-up cardiac catheterization rose with increasing heart rates during both RA and AV sequential pacing modes (Figure 7). Higher heart rates were also associated with significant increases in systemic arterial pressures and reductions in left ventricular systolic pressure and LVOT gradient. In addition, the systemic arterial pressures and cardiac output were significantly higher and left ventricular systolic pressure and LVOT gradient were lower during AV sequential pacing compared with values recorded at identical heart rates during RA pacing (Figure 7).

**Altered Hemodynamic and Electrocardiographic Findings in Chronic DDD Pacing**

The sinus rate at the follow-up study was similar to the sinus rate at the baseline study (79±12 and 79±17 beats per minute, respectively). However, the hemodynamic findings during sinus rhythm at the follow-up evaluation differed significantly from those during sinus rhythm at baseline: the PA, PCW, left ventricular end-diastolic and left ventricular systolic pressures, and LVOT gradient were significantly lower at the follow-up study (Figures 8 and 9). Similarly, the hemodynamic responses to alterations in heart rate and pacing mode differed significantly from those recorded at the baseline evaluation: The PA, PCW, left ventricular systolic pressures, and LVOT gradient were lower and systemic arterial pressures were higher during both RA and AV sequential pacing modes at heart rates of 100 and 120 beats per minute at the follow-up evaluation compared with the corresponding heart rates and pacing mode recorded at the baseline study (Figure 8). At the follow-up evaluation, cardiac output during RA pacing was similar to cardiac output recorded at the baseline study (Figure 8). Cardiac outputs during AV sequential
pacing at the follow-up evaluation were higher than those recorded during AV sequential pacing at the baseline study, but the differences were not significant (Figure 8). Figure 10 illustrates markedly reduced LVOT gradient during sinus rhythm in a patient after 3 months of DDD pacing. Figure 11 shows altered hemodynamic responses during RA and AV sequential pacing after chronic DDD pacing in an individual patient.

The 12-lead electrocardiogram recorded during normal sinus rhythm at the follow-up evaluation showed new T wave changes in 40 of the 44 patients. However, none of the patients developed bundle branch block, an increase in QRS duration, or a change in QRS axis.

**Follow-up.** The symptomatic benefits of DDD pacing have been maintained during a mean follow-up of 9±3 months (range, 3–13 months).

**Discussion**

Patients with obstructive HCM frequently complain of angina, dyspnea, palpitations, lightheadedness, pre-syncope, and syncope. These symptoms may respond to β-adrenergic blockers, verapamil, or disopyramide. However, some patients do not respond, and many who initially derive benefit develop side effects to the drugs or report symptoms that are refractory to pharmacotherapy.7-26 It has been our policy to recommend surgery to patients who remain severely limited after a trial of both types of medications.

Left ventricular septal myectomy is the most frequent operation that is performed to relieve LVOT obstruction. Mitral valve replacement is performed when the interventricular septum is thin or there are independent abnormalities of the mitral valve apparatus. These operations improve symptoms and exercise performance in about 60–70% of patients.9,26-38 Resting LVOT gradients are abolished or markedly reduced in most patients, a change associated with a reduction in left ventricular diastolic pressures and improvement in myocardial blood flow.38 However, left ventricular sep-
tal myectomy and mitral valve replacement have a reported 2–11% early mortality rate, and insufficient removal of muscle from the critical area of the septum can result in inadequate relief of LVOT obstruction. Furthermore, even in patients in whom resting LVOT gradient is abolished, many continue to have significant provovable outflow obstruction. Conversely, removal of excessive muscle can cause the devastating complication of interventricular septal defect. Left ventricular septal myectomy frequently results in creation of left bundle branch block, and about 5% of patients develop complete heart block postoperatively and require pacemakers. Finally, some patients develop left ventricular dysfunction postoperatively, presumably because of inadequate protection against ischemia of the massively thickened left ventricle; therefore, an important need remains for alternative methods of treating patients with obstructive HCM.

It has been appreciated for many years that right ventricular pacing can reduce LVOT gradients in HCM. The mechanism responsible for this finding is probably induction of paradoxical movement of the interventricular septum. However, because of frequently coexisting left ventricular diastolic dysfunction, the atrial transport mechanism is of critical importance to the maintenance of cardiac output and to minimize left atrial hypertension. Thus, pacemaker therapy of obstructive HCM requires implantation of an atrial synchronized ventricular pacing device capable of being programmed to a short AV delay to maintain the proper sequence of cardiac chamber activation and to ensure that the normal cardiac conduction system is bypassed.
by preexcitation of the right ventricular apex. Because all previous evaluations of DDD pacing involved few patients, it has been unclear as to the general applicability of this approach to the large group of HCM patients who have obstruction to left ventricular outflow and symptoms refractory to medical therapy.

We therefore initiated this study, which reports on the symptomatic and hemodynamic impact of DDD pacing in 44 consecutive patients with obstructive HCM. All were severely symptomatic and had failed to benefit from adequate doses of β-adrenergic blockers and verapamil. So that the therapeutic impact of DDD pacing could be adequately assessed, all patients with obstructive HCM who were candidates for operative relief of LVOT obstruction were enrolled into the pacing study. This included five patients in whom prior surgery had failed to relieve outflow obstruction.

DDD pacing eliminated or significantly improved symptoms in most patients with severe obstructive HCM. This impressive symptomatic result was associated with increased treadmill exercise performance and improved hemodynamic findings, that is, reduction of cardiac filling pressures and LVOT gradients and augmented cardiac output.

The design of the study permitted differentiation of the hemodynamic effects of AV sequential pacing from those caused by high heart rate. In this context, rapid heart rate per se resulted in modest reductions in LVOT gradient but only at the expense of marked increases in filling pressures and reductions in cardiac output. By comparison, AV sequential pacing caused significantly greater reductions in LVOT gradient with maintenance of higher cardiac outputs.

Of great interest was the unanticipated finding that major hemodynamic differences were apparent even when pacing was stopped after a period of chronic DDD pacing. When DDD pacing was temporarily discontinued at the follow-up evaluation and measurements were made in normal sinus rhythm, the left ventricular systolic, mean PA, PCW, and left ventricular end-diastolic pressures, and LVOT gradient were significantly lower than values recorded in normal sinus rhythm at the baseline study (Figures 8 and 9). Further evidence for the altered hemodynamic state was furnished by the different hemodynamic responses to right atrial and AV sequential pacing: At the follow-up evaluation, the left ventricular systolic pressures and LVOT gradients during rapid right atrial and AV sequential pacing modes

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**FIGURE 9.** Graph shows individual left ventricular outflow tract gradients at baseline study in normal sinus rhythm (NSR) (heart rate, 79±17 bpm, beats per minute) and at the follow-up evaluation during normal sinus rhythm (heart rate, 79±12 bpm) and dual-chamber (DDD) pacing (heart rate, 79±11 bpm).

**FIGURE 10.** Tracings show reduction of left ventricular outflow obstruction after chronic dual-chamber pacing recorded during sinus rhythm. At baseline (left panel), the left ventricular systolic pressure and left ventricular outflow tract gradient were 280 mm Hg and 90 mm Hg, respectively. At follow-up cardiac catheterization (right panel), the left ventricular systolic pressure and left ventricular outflow tract gradient, measured also in sinus rhythm, were reduced to 135 mm Hg and 15 mm Hg, respectively. I, II, III, V1, and V6, surface electrocardiographic leads.
were significantly less than those recorded for identical heart rates during the baseline study (Figure 8). This improved hemodynamic state was associated with increased exercise performance in sinus rhythm at the follow-up study. The hemodynamic findings were accompanied by new T wave electrocardiographic changes in most patients, similar to the electrotonic modulation of the T wave reported previously in normal subjects. Although the mechanisms responsible for the electrical and hemodynamic changes after chronic DDD pacing in our patients are not clear, it is known that the cellular and molecular structure of the heart is plastic; it may therefore be that the myocardium undergoes secondary cellular/molecular changes in response to altered pattern of electrical activation and/or reduced left ventricular systolic and diastolic pressures.

We conclude that DDD pacing results in significant symptomatic and hemodynamic improvement in most patients with obstructive HCM with severe symptoms that are refractory to drug therapy, and that the hemodynamic improvement persists even when DDD pacing is acutely discontinued. Based on the findings of this study, we propose that DDD pacing should be tried in all patients with obstructive HCM in whom symptoms have not responded to pharmacotherapy before considering left ventricular septal myectomy or mitral valve replacement (Figure 12). Further follow-up studies are required to establish 1) whether the patients continue to benefit over the long-term from DDD pacing; 2) the frequency with which the pacemaker devices need to be reprogrammed, and thus appropriate pacemaker follow-up; 3) whether acute hemodynamic changes during pacing studies at baseline cardiac catheterization identify patients who benefit most from DDD pacing; 4) the

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**FIGURE 11.** Tracings show altered hemodynamic responses to pacing after chronic dual-chamber pacing. At baseline study during right atrial pacing at 100 beats per minute (bpm) (upper left panel), the left ventricular systolic pressure and left ventricular outflow tract gradient were 240 mm Hg and 145 mm Hg, respectively. During atrioventricular (AV) sequential pacing at identical rate (upper right panel), the left ventricular systolic pressure and left ventricular outflow tract gradient were reduced to 220 mm Hg and 115 mm Hg, respectively. However, at the follow-up study, the left ventricular systolic pressure and outflow tract gradient during atrial pacing at the same rate as the baseline recordings were only 170 mm Hg and 10 mm Hg, respectively (lower left panel). Similarly, during AV sequential pacing (lower right panel), the left ventricular systolic pressure and outflow tract gradient were only 150 mm Hg and 10 mm Hg, respectively. I, II, III, and V6, surface electrocardiographic leads.

**FIGURE 12.** Chart of proposed management of patients with hypertrophic cardiomyopathy. *Exertional or postural symptoms; **left ventricular outflow tract gradient of all drugs ≥30 mm Hg at rest or ≥50 mm Hg after provocative maneuvers; ***repeat treadmill exercise tests to assess symptomatic improvement and to ensure that pacemaker programming allows preexcitation of the right ventricle throughout exercise, echocardiogram to establish a reduction in severity of anterior systolic motion of the mitral valve leaflet and left ventricular outflow tract velocities, and cardiac catheterization to document hemodynamic improvement. NYHA, New York Heart Association functional class; DDD, dual-chamber pacing; mth, month.
length of time that the reduction in LVOT gradients persist after cessation of pacing; and 5) the precise mechanisms contributing to the improved hemodynamic findings.

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