Permanent pacemakers have been used to treat patients with symptomatic bradycardia for 45 years. The earliest pacemakers paced only the ventricle and were used primarily for patients with complete heart block. The need for atrial pacing became apparent as pacing for sinus node dysfunction became more common. Initially, only single-chamber pacing was possible in the atrium, and this was a good therapeutic approach for patients with sinus node dysfunction and intact conduction from the atria to the ventricles. Dual chamber (DDD) pacemakers have been available for more than 20 years, and dual chamber rate-responsive (DDDR) pacemakers have been implanted for more than 15 years. With the availability of such universal pacemakers, implantation of a DDDR pacemaker has become the usual practice in the US for almost all patients except those with permanent atrial fibrillation. A conventional pacemaker paces the right atrium and the right ventricle. At nominal settings for atioventricular (AV) delay, such pacemakers will often pace the right ventricle with either fusion or complete capture even if intrinsic conduction is present. Only more recently has it become apparent that routine pacing of the right ventricle can be detrimental when it is not needed.

Concerns about deleterious effects of right ventricular pacing come in part from studies using devices capable of pacing the right ventricle in patients with no indication for the pacing. The Dual Chamber and single chamber ventricular pacemaker (VVI) Implantable Defibrillator Trial (DAVID)\(^1\) compared DDDR pacing with VVI pacing in patients with dual chamber implantable cardioverter-defibrillators (ICDs) in patients with an indication for an ICD, ejection fraction \(\leq 40\%\) but no indication for pacing. The hypothesis was that the dual chamber pacing devices would improve the incidence of congestive heart failure (CHF), atrial fibrillation, hospitalization, and death. There was no protocol programming requirement to avoid pacing the right ventricle in patients with no need for ventricular pacing. Therefore, at nominal AV delay settings, many patients had right ventricular pacing a high percentage of the time (60% of all ventricular beats) despite having no AV block indication for pacing. The result was an increased incidence of the composite end-point of hospitalization for CHF and death in patients programmed to DDDR mode, compared with those programmed to VVI mode with ventricular pacing at a low rate, and consequently no pacing at all in most patients (1% overall).

The Multicenter Automatic Defibrillator Implantation Trial II (MADIT II) also encountered unexpected problems related to worsening heart failure. The patients in MADIT II all had coronary artery disease and severe left ventricular dysfunction with ejection fraction (EF) \(<30\%\) but no indication for pacing. Patients with defibrillators lived longer, but had more heart failure admissions, which was out of proportion to their increased longevity.\(^2\) Unlike the MADIT,\(^2\) which involved only single chamber defibrillators, presumably programmed to avoid unnecessary ventricular pacing, MADIT II included dual chamber implantable heart defibrillators (ICDs) at the investigators’ discretion. At nominal settings, these too would be likely to capture the right ventricle. This is a hypothetical cause for the increase in heart failure in the defibrillator group.

Trials assessing the effect of atrial pacing in sick sinus syndrome patients have also been affected by the same problem. Andersen et al.\(^4\) compared single chamber right atrial pacing with single chamber right ventricular pacing in patients with sick sinus syndrome. They demonstrated significant benefit for atrial pacing with improved survival and a decreased incidence of thromboembolic events.

### References

atrial fibrillation, and congestive heart failure, especially after longer follow-up. The much larger Mode Selection Trial in Sinus Node Dysfunction (MOST), in which all patients had DDDR pacemakers implanted but were randomized to ventricular or dual chamber pacing, showed significant but less striking benefits in the incidence of atrial fibrillation and congestive heart failure. A possible explanation for the difference in the results between the two trials is that unintentional and unnecessary pacing of the right ventricle in the dual chamber group negated some of the benefits of sequential AV pacing compared with ventricular pacing.

This problem has taken so long to be recognized partly because patients who require pacing for symptomatic sinus bradycardia or heart block indications will benefit from an increase in heart rate. The clinical benefit of preventing severe bradycardia may overshadow any detrimental effect of asynchronous left ventricular activation due to right ventricular pacing. However, when unnecessary right ventricular pacing occurs in a patient who does not need an increase in rate, the effect can only be detrimental. That is the situation in patients without any bradycardia who receive dual chamber defibrillators, which at nominal settings will usually pace the right ventricle. The problem is made worse by the fact that many ICD patients, and all those in the DAVID and MADIT II studies, have reduced left ventricular function at baseline. Further reduction in left ventricular function from right ventricular pacing is more significant in these patients than in patients with conduction system disease and normal left ventricular function. In patients who have pure sinus node dysfunction but receive a dual chamber pacemaker rather than an atrial pacemaker, right ventricular pacing may decrease left ventricular ejection fraction and give up some of the gains from an increased atrial rate.

The advent of bi-ventricular pacing has highlighted the deleterious effect of left ventricular dysynchrony caused by native conduction system disease and the benefit of resynchronization, which is seen most clearly in patients with a left bundle-branch block (LBBB). Patients with CHF, low ejection fraction, and a wide QRS can have significant clinical improvement with biventricular pacing, which improves left ventricular synchrony, hemodynamics, and exercise tolerance. These beneficial effects have been shown in several clinical trials that were recently reviewed.\(^5\) Pacing the right ventricle in a patient with a normal conduction system artificially creates the same problem, which is more likely to be troublesome to a patient with poor left ventricular function initially. The Post AV Node Ablation Evaluation (PAVE) trial results were reported at the American College of Cardiology meeting in March 2004. In PAVE, patients with atrial fibrillation requiring AV node ablation were randomized to right ventricular or biventricular pacing. The trial showed a benefit for the biventricular pacing group despite somewhat better average left ventricular function than that in earlier biventricular pacing trials.

How can one avoid pacing the right ventricle? There are several possible pacing approaches to avoiding unnecessary right ventricular pacing:

- not pacing at all if pacing is not indicated, for example in an ICD patient;
- pacing only the atrium if AV conduction is intact; or
- pacing the atrium alone as much as possible if AV block is intermittent.

For patients with an indication for a device but no indication for pacing (that is, patients similar to those in the MADIT II or DAVID trials), VVI pacing at a low rate could be considered even if a dual chamber device is used for atrial arrhythmia discrimination. For patients with sinus node disease, the easiest way to pace only the atrium is to implant an atrial pacemaker. However, many practitioners are reluctant to implant an atrial pacemaker because of the potential for developing heart block in the future, although that is unlikely in properly selected patients, and because of the perception that atrial leads may be less reliable, hence the need for a ventricular lead as back-up. If a dual chamber pacemaker is implanted, programming a long fixed AV delay can avoid right ventricular pacing. This can sometimes be more effectively accomplished by the use of DDIR pacing rather than DDDR pacing to allow higher rate pacing without the limitations imposed by a long total atrial refractory period that may be needed with a long AV delay in the DDD or DDDR mode to avoid the possibility of pacemaker-mediated tachycardia. AV delay hysteresis, which lengthens the AV delay when ventricular sensing is occurring, can also provide intrinsic conduction without programming an excessively long basal AV delay. This is a more important issue for the patient with intermittent AV block who needs a shorter AV delay when native conduction fails. A search hysteresis function is helpful in this situation to restore atrial pacing when intrinsic conduction resumes. These approaches may not work for every patient because there are a small minority of patients who cannot tolerate atrial pacing with a long AV delay because of symptoms caused by poorly timed atrial contraction that are similar to pacemaker syndrome caused by ventricular pacing.

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The most sophisticated approach yet available for atrial pacing with a dual chamber pacemaker is a pacing scheme implemented in new ELA Medical pacemakers. Called AAIsafeR, it provides true atrial inhibited (AAI) or atrial inhibited, rate-modulated (AAIR) pacing until a pause of two or three seconds with non-conducted atrial beats or persistent 2:1 AV block, indicating the onset of AV block and the need to switch to mode DDDR pacing. Search algorithms allow the pacemaker to return to AAIR pacing even when there is a substantial first-degree AV block, but too frequent switching causes permanent dual chamber pacing. In a one-month trial of this algorithm in 43 patients who were divided evenly between sinus node disease and paroxysmal AV block, Fröhlig et al. found that in patients with either temporary or no mode switching, there was 0.2% ventricular pacing, compared with 73% in patients who switched permanently to dual chamber pacing. Interestingly, the percentage of patients permanently switching to dual chamber pacing was independent of pacing indication (six in 22 with sinus node disease, nine in 21 with heart block).

In some patients, right ventricular pacing cannot be avoided because of too frequent second- or third-degree AV block. In such patients, biventricular pacing may be an alternative, and it might be considered at initial implant when continuous ventricular pacing is anticipated for a bradycardia indication if there is pre-existing left ventricular systolic dysfunction. This approach is not yet supported by consensus guidelines or by a lot of data, but the PAVE trial is a first step in this direction.

In summary, pacing the right ventricle should be avoided when at all possible to prevent unnecessary left ventricular dyssynchrony, which is particularly harmful to patients with left ventricular dysfunction. A number of pacemaker or ICD programming options to favor intrinsic conduction are available in all devices, but advanced approaches such as AAIsafeR, may prove to be more effective. If ventricular pacing cannot be avoided, biventricular pacing may be considered, either as treatment for the pacemaker patient who has developed heart failure or prophylactically in the patient with left ventricular dysfunction and with bradycardia due to second- or third-degree AV block.