Introduction

The first fully implantable pacemaker was placed in a person in 1958. The first artificial pacemaker implantation in a dog was described by Dr. James Buchanan more than 40 years ago. Since that time, transvenous pacing has become a procedure commonly performed by veterinary cardiologists in the treatment of complete atrioventricular (AV) block, high-grade second-degree AV block, sick sinus syndrome, and atrial standstill. It is a minimally invasive surgical procedure in which pacing leads are most commonly advanced into the right ventricular apical endocardium via surgical cutdown over the jugular vein.

Initially, pacemakers provided asynchronous pacing, with no sensing of inherent heartbeats and no alteration of the pacing impulse in response to inherent beats. These early pacemakers simply paced 100% of the time. Subsequent pacemakers were created to pace in a ventricular demand mode (VVI pacing): the pacemaker sensed inherent beats and could either inhibit the pacing impulse or trigger a pacing impulse within the ventricular myocardium to allow for ventricular depolarization (FIGURE 1). Although this mode of ventricular pacing was better, some patients did not respond well, experiencing continued syncopal or near-syncopal events, dizziness, and, sometimes, congestive heart failure. The term pacemaker syndrome was coined to refer to a complex of clinical signs and symptoms related to the potential adverse hemodynamic and electrophysiologic consequences of ventricular pacing in human patients. Neurologic symptoms or lethargy and symptoms suggesting low cardiac output or congestive heart failure may be indicative of pacemaker syndrome in people; corresponding clinical signs may lead to suspicion of this syndrome in animals.

Physiologic Pacing

AV dyssynchrony and lack of rate modulation were initially identified as causes of pacemaker syndrome. Since the initial descriptions and development of pacing techniques, technological advances have enhanced the sophistication of cardiac pacemakers to allow proper sequencing of atrial and ventricular contraction and physiologic rate modulation. The restoration of AV synchrony by pacing was branded early on as physiologic pacing in humans because it mimics the normal sequence of AV activation. Physiologic rate modulation has allowed patients to have lower heart rates at rest and higher heart rates with exercise. In humans, the importance of atrial contribution to cardiac output has been demonstrated in a variety of patient groups as well as at different heart rates.

While single-chamber ventricular pacing prevents bradycardia and death from ventricular standstill, dual-chamber pacing may...
be able to better emulate normal cardiac physiology by restoring AV synchrony and matching the ventricular pacing rate to the sinus rate. In patients with sick sinus syndrome, periods of sinus arrest, and a normally functioning AV node, synchronization between the atria and ventricles can easily be accomplished by using atrial leads (FIGURE 2). For patients with AV nodal disease, AV synchrony can be maintained by using dual-lead systems, in which one lead is placed in the right atrium and the other lead is placed in the right ventricle (FIGURE 3). In this situation, both leads are capable of sensing inherent beats as well as pacing the chamber in which they are located.

Dual-chamber pacing can also be accomplished using a single-lead system that includes a floating atrial electrode in the right atrium and a ventricular pacing electrode in the right ventricular apical endocardium (FIGURE 4). This system can sense inherent sinus node depolarizations (P waves) and deliver ventricular pacing impulses in response.

Maintenance of AV synchrony by using either dual-chamber pacing systems or atrial pacing systems has reduced clinical symptoms and improved quality of life in people with complete AV block and sick sinus syndrome and offers significant clinical improvement compared with single-chamber ventricular pacing. In short- and long-term studies, AV synchrony improves stroke volume, raises systolic blood pressure, reduces right atrial pressure and pulmonary capillary wedge pressure, and is less likely to elicit cardioinhibitory reflexes compared with single-chamber ventricular pacing. Interestingly, studies in humans have not shown reductions in mortality with rate-modulated dual-chamber ventricular pacing compared with rate-modulated VVI pacing.

Despite the ability to restore physiologic heart rates and maintain AV synchrony in patients with bradyarrhythmia, current pacing techniques could still be improved. The drive to improve pacing practices has pushed human and veterinary electrophysiologists to rethink what is meant by physiologic pacing. The most common pacing site, the right ventricular apex (RVA), allows for easy and secure endocardial lead placement but is considered suboptimal for pacing by some electrophysiologists. During normal sinus rhythm or atrial pacing, impulse activation of the ventricles is characterized by minimal asynchrony, activation of the left ventricle (LV) before the right ventricle (RV), and activation of apical myocardial cells before basal cells. During RVA pacing, the activation sequence deviates significantly from the physiologic one and is associated with a considerable depression of LV function, a high incidence of myocardial perfusion defects, regional changes in tissue perfusion, increases in tissue catecholamine activity, disorganization of myofibers and subcellular elements, and cellular alterations ranging from mitochondrial morphologic changes to degenerative fibrosis and fatty deposits in human patients.

Where is the Ideal Pacing Site?
Methods of maximizing the clinical benefits of pacing therapy for bradyarrhythmias have traditionally focused solely on the features of the impulse generator. With renewed appreciation for the important role that the pacing site may play in patient outcome,
Cardiac Pacing Site Optimization

focus is now shifting to identifying the optimal or ideal site for pacing and delivering leads to that location. The fact that RVA pacing causes LV dysfunction was recognized as early as 1925.18 During both sinus and atrial pacing, the Purkinje system contributes significantly to rapid electrical activation of the ventricles, whereas the impulse from ventricular pacing is almost exclusively conducted more slowly through myocardium. When Wiggers18 examined a variety of stimulation sites on the epicardial surface of the canine heart, he found that the site of stimulation exerted considerable influence on LV function and postulated that the degree of functional impairment was inversely related to the proximity of the stimulation site to the His-Purkinje system. The question has now arisen: if the RV A is unsuitable for long-term ventricular pacing, what is the alternative?

In an effort to identify the optimal or ideal pacing site that will not worsen cardiac function, alternate sites in the RV have been investigated: the outflow tract, septum, and free wall. Studies evaluating these alternate pacing sites have produced conflicting and controversial results.19-21 His-bundle pacing has been of theoretical interest for many years. The idea of delivering a pacing impulse directly into the cardiac conduction system is attractive because of the possible hemodynamic benefits that could be obtained by a normal activation sequence. However, the small size and anatomic position of the His bundle have made this approach difficult.

Cardiac resynchronization using biventricular pacing is sometimes recommended as a treatment for congestive heart failure in people. This recommendation is based on the concept that heart failure can be exacerbated by dysynchrony within the conduction system and that resynchronizing the contraction pattern can improve cardiac function.21,22 In this situation, simultaneous or near-simultaneous transvenous stimulation pacing of the RV and LV is possible using traditional pacing sites (the RV and right atrium [RA]) and a third lead placed within the coronary sinus and into a left lateral coronary vein overlying the LV free wall (FIGURE 5). Such a pacing strategy has not yet been shown to protect or improve LV performance in patients requiring pacing for bradyarrhythmias.

In an ongoing clinical trial, dogs with naturally occurring third-degree or complete heart block in need of pacing therapy are being randomly assigned to three treatment groups with differing combinations of long-term pacing leads: (1) dual-chamber RA-RVA pacing, (2) dual-chamber RA-LV free wall pacing, and (3) dual-chamber biventricular pacing. Synchronization is assessed by electrocardiograms and tissue Doppler imaging, and cardiac function is assessed by echocardiographic determination of stroke volume, cardiac output, and ejection fraction. This study is under way at the University of Florida Veterinary Medical Center. Results are expected in September 2012.

References