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THE PRESENT AND FUTURE

STATE-OF-THE-ART REVIEW

Cardiac Pacemakers: Function, Troubleshooting, and Management

Part 1 of a 2-Part Series

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ABSTRACT

Advances in cardiac surgery toward the mid-20th century created a need for an artificial means of stimulating the heart muscle. Initially developed as large external devices, technological advances resulted in miniaturization of electronic circuitry and eventually the development of totally implantable devices. These advances continue to date, with the recent introduction of leadless pacemakers. In this first part of a 2-part review, we describe indications, implant-related complications, basic function/programming, common pacemaker-related issues, and remote monitoring, which are relevant to the practicing cardiologist. We provide an overview of magnetic resonance imaging and perioperative management among patients with cardiac pacemakers. (J Am Coll Cardiol 2017;69:189–210)

A BRIEF HISTORY OF CARDIAC PACING

Cardiac pacing, electrical stimulation to modify or create cardiac mechanical activity, began in the 1930s with Hyman's "artificial pacemaker" (his term), in which a hand crank created an electric current that drove a DC generator whose electrical impulses were directed to the patient's right atrium through a needle electrode placed intercostally. At that time, Hyman faced professional skepticism, litigation, and accusations of creating "an infernal machine that interferes with the will of God," and he never found a manufacturer for his machine (1).

After World War II, public perception changed and daring pioneers made great advances. Large, external, alternating current-powered pacemakers tethered to an extension cord gave way to battery-powered, transistorized, "wearable" pacemakers (**Central Illustration**). The birth of pacing was linked to cardiac surgery, which was burgeoning. In 1957, at the University of Minnesota, C. Walton Lillehei had performed over 300 open-heart operations on young adults and children with congenital defects. Dr. Lillehei and coworkers developed a myocardial wire for post-operative pacing. On October 31, 1957, a municipal power failure in Minneapolis lasted 3 h and led to the tragic death of a baby (2). The following day, Dr. Lillehei asked Earl Bakken, a hospital equipment engineer, to build a battery-powered device to prevent future tragedies. Bakken modified a circuit for an electronic metronome he had seen in the April 1956 issue of *Popular Electronics* that used transistors, which had been invented 10 years before. He modified the 2-transistor circuit so that the electrical pulses would pace the heart, rather than power a speaker. The device was immensely successful. He named the company he founded Medtronic. Other innovations would lead to the founding of other, now familiar manufacturers.

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ABBREVIATIONS AND ACRONYMS

CIED = cardiac implantable electronic device

CS = coronary sinus

PMT = pacemaker-mediated tachycardia

PVARP = post-ventricular atrial refractory period

RV = right ventricle

TARP = total atrial refractory period

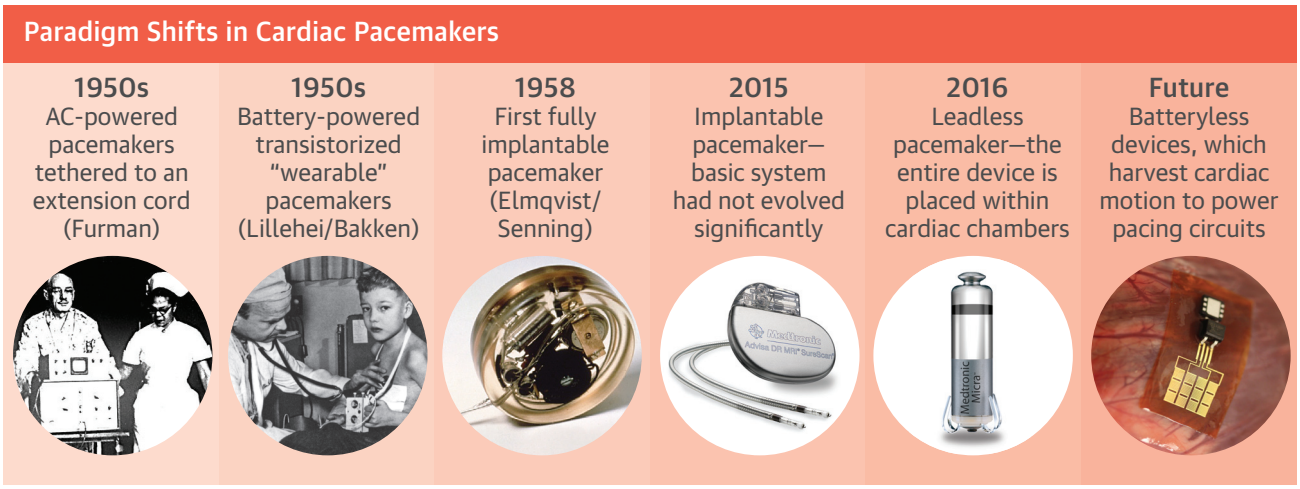
In 1960, Rune Elmqvist and Ake Senning of Stockholm placed the first fully implantable pacemaker in Arne Larsson. Larsson's wife had pleaded with Senning to use the experimental technology to help her desperately ill husband, who had complete heart block and frequent Stokes-Adams syncopal attacks. To avoid publicity, the initial implantation was performed at night, when the operating rooms were empty. The original system lasted 8 h. Arne Larsson ultimately went on to undergo over 20 pacemaker replacements, and he outlived both his surgeon and device engineer. He was an advocate for pacing until his death at 86 years of age in 2002 (3).

Although significant advances in pacing technology were developed over the next 50 years, including multichamber pacing, rate responsiveness, device size reduction, internet-based remote monitoring, and marked increases in battery longevity, the basic system paradigm of an extravascular pulse generator connected to 1 or more leads that traverse the venous system to contact myocardial tissue would not change for 50 years (**Central Illustration**). However, many pacemaker-related complications (infection, thrombosis, lead failure, and pneumothorax) are related to this basic construct, particularly the leads. This has led to a paradigm shift: the development of a leadless pacemaker, in which the entire device is placed within cardiac chambers. Batteryless devices, which harvest cardiac motion to power pacing circuits, are on the horizon as a coming paradigm shift. In this first part of the 2-part review of cardiac pacing, we explore the state-of-the-art: the basics of pacing physiology, pacing modes and indications, periprocedural management, complications, basic troubleshooting, perioperative management for nonpacemaker procedures, and cardiac magnetic resonance imaging (CMR) of patients with pacemakers. In part 2 of our review (4), we will examine recent advances and future directions, including resynchronization for heart failure, His bundle pacing, remote monitoring, and leadless and batteryless devices.

BASICS OF CARDIAC PACING

Normal cardiac activity begins in the sinus node, where cells with intrinsic automaticity act as pacemaker cells. Electrical wave fronts then spread across the atria to the atrioventricular (AV) node, which they pass through to enter the His-Purkinje system to rapidly spread to and depolarize the ventricles (**Figure 1**). When intrinsic cardiac automaticity or

CENTRAL ILLUSTRATION **An Overview of the History of Cardiac Pacing**



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Historically, pacing developed using large, external, alternating current (AC)–powered devices, which subsequently evolved to "wearable" transistorized battery powered pacemakers—both comprise the era of external devices. A paradigm shift occurred with the introduction of the entirely implantable pacemaker, composed of an extravascular pulse generator connected to a transvenous lead in contact with the myocardium. This paradigm continues to this day. An emerging and rapidly developing new paradigm is that of leadless pacemakers, which are available for clinical use. Batteryless pacemakers that harvest cardiac mechanical motion to generate current, or that modify or add cells to introduce biological pacing activity, are under active investigation.