Physiologic Sensors in Pacemakers
How Do They Work and How Many Do We Need?

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KEYWORDS

• Physical sensor • Rate adaptation • Pacemaker • Hemodynamic sensor

KEY POINTS

- Sensor-based rate adaptation is an essential part of modern cardiac pacing therapy.
- The benefits of rate-adaptive ventricular pacing in comparison with fixed-rate ventricular pacing have been demonstrated in many clinical studies, but the additional benefit of rate adaptation in dual-chamber pacemaker systems (DDDR vs DDD) has not been clearly established despite large clinical studies.
- The advantage of dual-sensor or multiple-sensor systems over a single sensor is not yet certain and likely varies depending on specific patient cohorts.
- The advantage of dual-/multiple-sensor pacing is more likely to be obtained in patients with an active lifestyle. Whether the complexity of such systems (ie, requiring more attention to programming and their added cost) outweigh any physiologic benefit are questions that are not likely to be resolved for some time.
- The future direction of hemodynamic sensors will be toward reliable assessment of crucial hemodynamic variables such as preload, afterload, left ventricular ejection fraction and stroke volume.

INTRODUCTION

The first implantable cardiac pacemakers were designed to pace at a fixed rate without sensing the patient's intrinsic heart rhythm. These fixed-rate devices were primarily used for ventricular pacing (VVI mode); atrial pacing (AAI mode) was a possibility if atrioventricular conduction was adequate, but was only rarely attempted by most implanters owing to instability of passive-fixation endocardial pacing leads, and both the difficulty in implantation and poor longevity of epicardial pacing leads (**Box 1**). Subsequently, devices that sensed native atrial activity were introduced (eg, VDI, DDD modes) in conjunction with active-fixation lead technologies. These latter pulse-generator and lead systems provided a more physiologic approach to pacing, but their rate-adaptive capability was undermined by the frequent presence of native and/or drug-induced sinus node dysfunction in many paced patients. Furthermore, in the presence of permanent atrial fibrillation or other atrial tachycardias, atrial electrical activity was not a desirable sensing option.

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Box 1
Pacing modes cited in this article

AAI	Atrial pacing; atrial sensing and inhibition
AAIR	Atrial pacing; atrial sensing and inhibition; rate-modulated pacing
VVI	Ventricular pacing; ventricular sensing and inhibition
VVIR	Ventricular pacing; ventricular sensing and inhibition; rate-modulated pacing
DDD	Dual-chamber pacing; dual-chamber sensing and inhibition; tracking of the atrium
DDDR	Dual-chamber pacing; dual-chamber sensing and inhibition; tracking of the atrium; atrioventricular sequential rate modulation
DVI	Dual-chamber pacing; ventricular sensing and inhibition; no tracking of the atrium
DVIR	Dual-chamber pacing; ventricular sensing and inhibition; no tracking of the atrium; atrioventricular sequential rate modulation

The first sensor-based rate-adaptive pacemaker was introduced in the 1970s by Italian researchers, and used alterations of blood pH during exercise to effect changes in pacing rate.[1] This system did not become widely used, but the concept triggered subsequent technological development, and rate-adaptive pacing systems using one or other form of "physiologic" sensor began to receive broad acceptance in clinical practice in the mid-1980s. Not only have a wide variety of sensor systems been developed, but sensor combinations have also been introduced in an attempt to optimize physiologic benefits.[2,3] This article reviews the technology and clinical utility of the most widely used rate-adaptive sensor systems and sensor system combinations for implantable cardiac pacemakers.

SENSORS FOR RATE-ADAPTIVE PACING

In the 1980s[4] physiologic sensors were categorized into 5 groups based on the accuracy of their relationship to oxygen consumption: (1) those measuring oxygen consumption directly, such as oxygen uptake; (2) sensors having a linear relationship with the sensors of the first group, such as cardiac output, atrioventricular oxygen difference, or minute ventilation (MV)[5,6]; (3) those having a linear relationship with sensors of the second group, such as heart rate, stroke volume, mixed oxygen saturation, tidal volume, or respiratory rate[7,8]; (4) sensors dependent on sympathetic activity and circulation catecholamines, such as right ventricular dP/dt and QT interval[9]; and (5) those using physiologic feedback from metabolism, such as mixed venous lactate and bicarbonate levels or central venous pH.[10] Subsequent work introduced an additional group of physical sensors that corresponded at best only indirectly to metabolic state, but rather more directly on body movement (ie, activity sensors and accelerometers).[11–13]

Despite the great variety of sensors that have been designed and investigated in the past, only a few sensors for rate-adaptive application proved to be commercially successful and remain clinically available. Activity sensing (mainly accelerometer-based), MV (respiration-based), and so-called closed-loop stimulation sensors using electrical bioimpedance are currently the primary surviving systems. Sensors for QT interval (more accurately termed Stim-T interval) detection or peak endocardial acceleration (PEA) are much less widely used.

Activity Sensors

Sensors capable of responding in a more or less graduated fashion to vibration or acceleration forces applied to the pacemaker body by surrounding tissues are referred to as activity sensors. Activity sensing is most frequently used for rate-adaptive pacing, in large part because of its simplicity in application, robustness, and compatibility with standard pacing leads. Although these may be the least "physiologic" sensors, they exhibit high reliability as well as excellent long-term stability.

The first activity sensor used in a commercially successful pacemaker (Activitrax; Medtronic Inc, Minneapolis, MN, USA; **Fig. 1**A) was a piezoelectric crystal designed to detect vibration generated by body movement.[14] The vibration of the human body, and in particular the muscle mass and skeleton in proximity to the pacemaker, are detected by a piezoelectric crystal bonded to the interior surface of the pulse generator casing that faces the pectoral muscle (see **Fig. 1**B). Vibration is sensed from mechanical forces through tissue/skeleton contact. The slight deformation of the piezoelectric crystal generates a small electric voltage. Depending on a predetermined programmable threshold and the extent of body motion, the voltage may be large enough to be counted as signals and be used for triggering alterations in the pacing rate. The amount of tissue contact and the coupling mass of mechanical force in each