Advances in Short-Term Cardiac Pacing Technology: From Bulky Beginnings to Bioresorbable Future

Su Kyung Oh

The Graduate School
Yonsei University
Department of Medical Device Engineering and Management

Advances in Short-Term Cardiac Pacing Technology: From Bulky Beginnings to Bioresorbable Future

A Master's Thesis Submitted
to the Department of Medical Device Engineering and Management
and the Graduate School of Yonsei University
in partial fulfillment of the
requirements for the degree of
Master of Health Engineering

Su Kyung Oh

June 2024

This certifies that the Master's Thesis of Su Kyung Oh is approved.

Thesis Supervisor Choi, Yeon Sik

Thesis Committee Member Kim, Hyung Jin

Thesis Committee Member Bak, Seong Min

The Graduate School
Yonsei University
June 2024

감사의 글

많은 분들의 도움과 격려로 이 논문을 완성할 수 있었음에 깊은 감사의 말씀을 전하고자 합니다.

먼저, 최연식 지도교수님께 진심으로 감사를 드립니다. 업무와 병행하며 시작한 학업에서 교수님의 연구 주제와 저의 현장 업무의 교차점에서 만난 듯한 그날은 제 2 년간의 학업 과정 중 가장 기억에 남는 날로 남아 있습니다. 그날을 시작으로 저에게 아낌없는 지도와 조언으로 이끌어 주신 덕분에 좋은 논문이 나올 수 있었습니다. 바쁘신 와중에도 항상 꼼꼼하고 친절하게 이끌어 주셔서 진심으로 감사드립니다.

또한, 심사위원 김형진 교수님, 박성민 교수님께도 감사의 말씀을 드립니다. 귀중한 시간을 내어 제 논문을 심사해 주시고, 유익한 피드백을 주셔서 연구의 완성도를 높일 수 있었습니다.

가장 큰 힘이 되어 준 부모님과, 수현언니에게도 말로 다 할 수 없는 감사를 전합니다. 변함없는 사랑과 지지가 있었기에 업무와 병행하여 때로는 지치고 포기하고 싶을 때 마다 포기하지 않고 끝까지 마무리할 수 있게 해 주었습니다. 제가 어떤 상황이던, 어떤 모습이던 한결 같은 사랑에 지금의 제가 있음을 전합니다.

아울러, 연구를 함께 도와주신 서형호 선생님과, 학업을 마칠 수 있도록 업무면에서 지원과 도움을 주신 Johnson and Johnson MedTech Korea 선후배님들 및 자문을 구했던 모든 동료분께 감사를 표합니다.

모든 분들의 지원과 사랑에 감사드리며, 이 과정을 통해 배운 지식과 자산을 가지고 좋은 영향력을 끼치며 살아가겠습니다.

Table of Contents

List of Figures

List of Table

Abstract

Advances in Short-Term Cardiac Pacing Technology: From Bulky Beginnings to Bioresorbable Future

Temporary cardiac pacemakers, unlike their permanent counterparts, are externally applied devices delivering electrical impulses through skin-penetrating electrodes (i.e., leads) for short-term heart rate regulation, notably in emergencies or specific medical interventions. Despite their prevalence in medical practice, temporary pacemakers have historically received less attention than permanent ones due to their transient nature. However, recent developments, including novel bioresorbable pacemakers, have spotlighted the solutions for limitations of existing temporary pacing and potential remedies.

This thesis comprises two comprehensive chapters. The first extensively examines current commercialized temporary pacemakers, pivotal for providing demand-based atrial and/or ventricular pacing during transient bradycardia episodes lasting days or weeks. Initial sections elucidate the electrophysiological underpinnings of bradycardia, while subsequent portions delineate patient demographics necessitating temporary pacemaker implantation, dissecting scenarios involving extrinsic and intrinsic bradycardia causes. Additionally, a historical overview of temporary pacing devices is provided, encompassing various designs tailored to specific patient profiles or technological advancements. The chapter concludes with an exhaustive review of clinical complications encountered during device implantation, operation, and extraction procedures.

The second chapter explores recent breakthrough in temporary cardiac pacing technology, with a particular focus on a novel bioresorbable material-based wireless device. Building upon insights gleaned from the first chapter, this section delves into the motivating factors behind these

innovations, such as advancements in bioresorbable electronic materials, leadless and battery-free pacing therapies, and closed-loop systems for autonomous pacing.

Through this thesis, a comprehensive review of temporary cardiac pacemakers is presented, spanning from their historical evolution to contemporary state-of-the-art solutions. Moreover, the thesis offers the future trajectory of temporary pacing, envisioning advancements in materials, device architectures, and pacing methodologies.

Keywords: Temporary, cardiac pacing, Temporary cardiac pacemaker, bradycardia, bioresorbable, material, closed-loop, battery-free

CHAPTER 1: Introduction

Temporary cardiac pacing serves as a critical intervention in life-threatening bradycardias, ensuring adequate hemodynamics until the arrhythmia resolves or long-term therapy can be initiated, thereby potentially saving lives. However, compared to permanent pacemaker systems, the progress in temporary pacing technology has been somewhat limited, with persistent risks associated with structural design and complications such as percutaneous lead infections and the risk of lead removal.

Recent strides in medical innovation have led to the development of a groundbreaking bioresorbable material-based temporary cardiac pacemaker, offering promising solutions to address longstanding issues in current temporary pacing devices.

This thesis offers a comprehensive examination of advancements in short-term cardiac pacing technology, spanning from its historical evolution to recent breakthroughs. The initial chapter delves into the electrophysiological mechanisms underlying bradycardia, while subsequent sections analyze patient demographics necessitating temporary pacemaker implantation, dissecting scenarios involving both intrinsic and extrinsic bradycardia causes. A detailed historical overview of temporary pacing devices is provided, with a focus on materials and structural design perspectives. Furthermore, the chapter meticulously highlights the complications encountered in clinical settings, ranging from device implantation to operation and extraction, along with the associated risks and limitations.

The second chapter introduces the novel bioresorbable pacemaker as a recent breakthrough in temporary cardiac pacing technology. Advancements in bioresorbable electronic materials, alongside innovations in leadless and battery-free pacing therapies, and the implementation of closed-loop systems for autonomous pacing, exemplify how this device addresses longstanding challenges in temporary cardiac pacing technology. The thesis concludes by summarizing its findings and discussing potential avenues for future research in this field.

CHAPTER 2: Target Patients

In general, temporary cardiac pacing is primarily utilized for patients with (i) reversible bradycardia for prophylactically, (ii) irreversible bradycardia as bridge stage to implantation of a permanent pacemaker, or, rarely, (iii) treatment of tachycardia[1].

2.1 Mechanisms of bradycardia

Bradycardia, also known as bradyarrhythmia, refers to a resting heart rate that falls below 50 beats per minute (BPM) in adults, and it leads to symptomatic discomfort and/or significant hemodynamic compromise[1,2]. Globally, the prevalence of bradycardia ranges from 0.5% to 2.0% in the general population[3]. Figure1 It is notably related to more common age and gender, particularly those aged 65 years and above[3] and male, respectively[4].

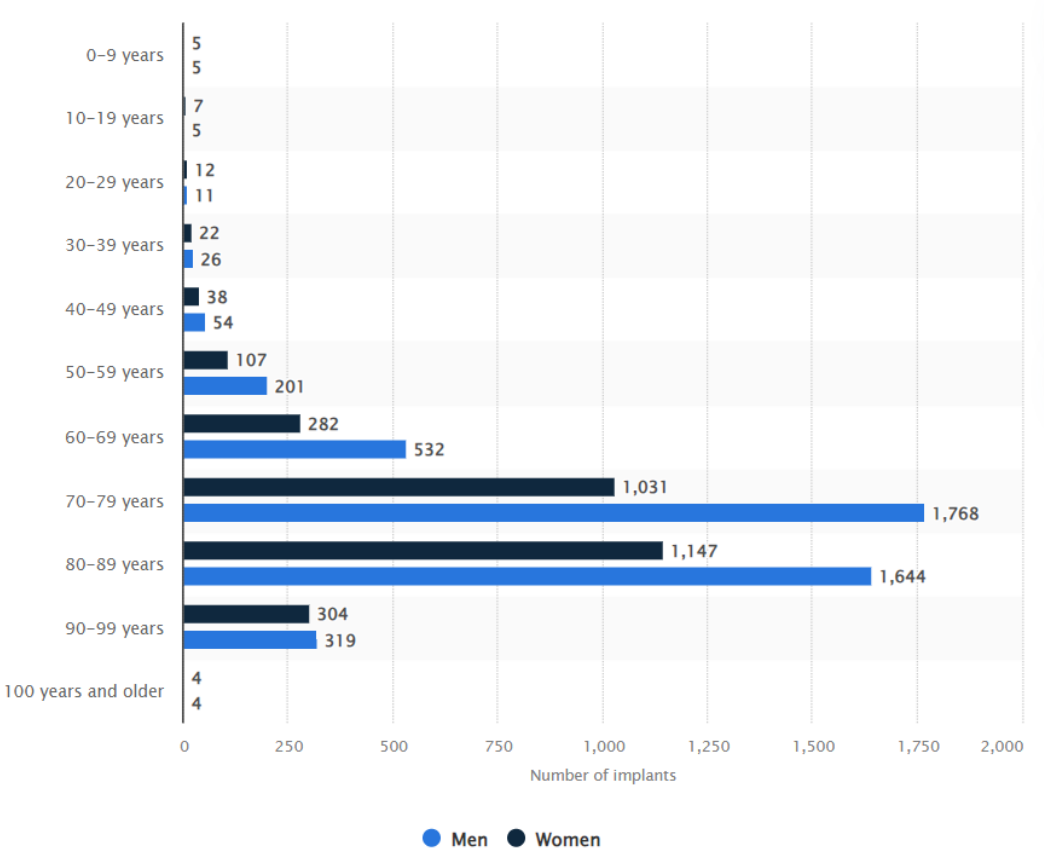


Figure 1. Number of new pacemaker implants in 2021[4].

The electrophysiological mechanisms of bradycardia are related to the automaticity and conduction systems: (i) sinoatrial (SA) node dysfunction, (ii) atrioventricular (AV) node block, and (iii) bundle branch block.

The schematic illustration provided in Figure 2 depicts the anatomical location of each component of the cardiac conduction system. The SA node (i.e. sinus node) serves as the heart's intrinsic pacemaker and is situated at the junction of the superior right atrium and the superior vena cava. Responsible for generating rhythmic electrical impulses, the SA node initiates each heartbeat in a normal sinus rhythm. The AV node plays a crucial role in the precise timing of electrical conduction from the atria to the ventricles. Positioned in the lower portion of the interatrial septum, the AV node introduces a slight delay in the electrical signal, allowing for sequential contraction of the atria followed by the ventricles, ensuring efficient blood flow. Subsequently, the electrical impulse travels through the Bundle of His, which divides into the right bundle and left bundle located within the interventricular septum. Finally, the impulse propagates through the Purkinje fibers, facilitating coordinated depolarization and contraction of the right and left ventricles, contributing to effective pumping of blood throughout the body[2,5].

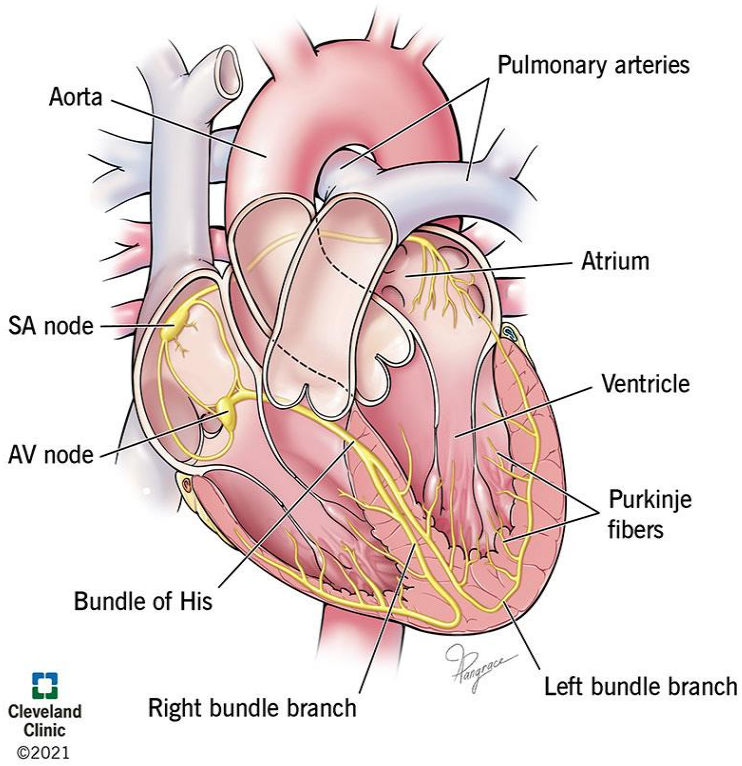


Figure 2. Diagram of the cardiac conduction system[6].

2.1.1 Sinoatrial (SA) node dysfunction

Disorders affecting SA node automaticity and conduction can lead to bradycardia, a condition known as SA node dysfunction. In the United Kingdom, the prevalence of SA node dysfunction is approximately 0.03%[7], with a higher incidence among the elderly population, affecting approximately 1 in every 600 cardiac patients over the age of 65[8]. This age-related increase in prevalence is often attributed to progressive fibrosis of the sinus nodal tissue and surrounding atrial myocardium, resulting in abnormalities in impulse formation and propagation[2]. Contributing factors may include cell atrophy, ischemia, coronary artery disease, and ion channel remodeling[9]. SA node dysfunction manifests as abnormalities in automaticity or conduction, or a combination of both. Automaticity refers to the SA node's ability to generate spontaneous depolarizations at a rate faster than other latent cardiac pacemakers, while conduction involves the transmission of these impulses through and out of the SA node. Delays or failures in conduction can occur within the sinus node itself or at its junction with the atrium in the perinodal tissue[9]. Figure 3 provides an organized overview related to SA node dysfunctions.

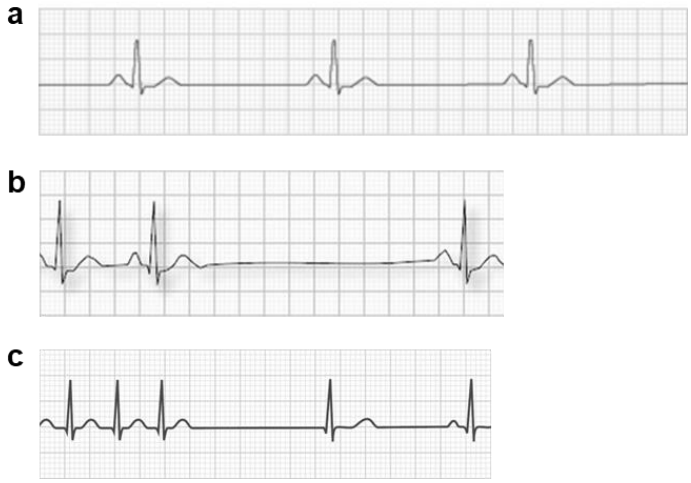


Figure 3. ECG diagrams resulted from sinoatrial node dysfunction: (a) sinus bradycardia, (b) sinoatrial block and sinus arrest, (c) tachycardia-bradycardia syndrome, which is generally associated with the marked pause following the cessation of paroxysmal supraventricular tachycardia that occur in the setting of sinus bradycardia.

2.1.2 Atrioventricular (AV) node block

While structural abnormalities present at birth, such as congenital heart diseases, can predispose individuals to AV block, most cases develop because of functional and/or anatomical changes that occur with aging. Theoretically, conditions such as heart attacks or coronary artery disease, along with fibrosis within the heart, can lead to conduction disturbances in various regions, including the AV node, Bundle of His, bundle branches, or fascicles[10].

Figure 4 presents ECG diagrams illustrating various types of AV node block. First-degree AV node block is characterized by prolonged conduction with 1:1 impulse transmission, often asymptomatic and typically not requiring treatment. Second-degree AV node block exhibits less than 1:1 impulse transmission, potentially causing symptoms such as dizziness of fainting. This type is further classified into Type I and II. Type I, also known as Mobitz Type I or Wenckebach block, is marked by progressive prolongation in A-V conduction time preceding the blocked impulses. Conversely, Type II, or Mobitz Type II, involves sudden failure of conduction without changes in conduction time of conducted beats preceding or following the non-conducted one. Third-degree AV node block, or complete AV node block, signifies complete loss of impulse transmission, severing communication between the sinoatrial node and the ventricles. Notably, in the absence of normal impulse transmission, ventricular electrical activity may be sustained by an escape rhythm originating from an ectopic focus. This phenomenon is critical, as escape rhythms may fail to manifest, emerge transiently, or produce an inadequate heart rate. Consequently, third-degree AV block poses a significant risk of syncope or even cardiac arrest, rendering it a life-threatening condition[5].

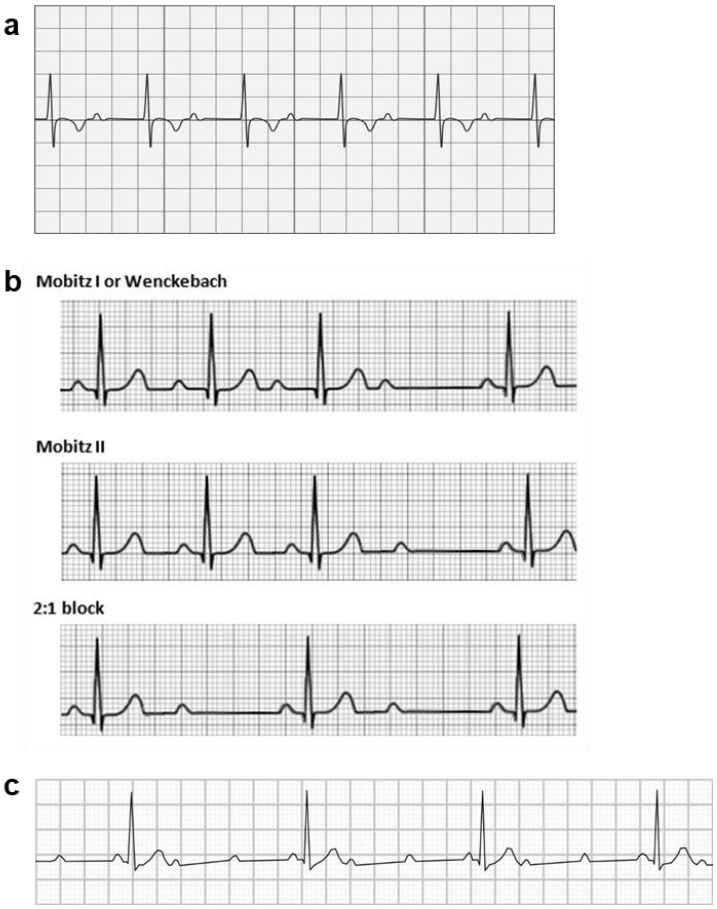


Figure 4. ECG diagrams resulted from AV blocks. (a) first-degree AV block, (b) second-degree AV block, (c) third-degree AV block.

2.1.3 Bundle branch block

Bundle branch block refers to a partial or complete interruption of impulse conduction in one of the bundle branches of the heart's electrical conduction system. Similarly, fascicular block involves interruption in a hemi fascicle of the left bundle. It's important to note that these disorders often coexist. While there are typically no symptoms associated with bundle branch or fascicular blocks, their presence may indicate an underlying heart disorder.

As shown in Figure 5, bundle branch block can manifest in various forms, including right bundle branch block (RBBB), left bundle branch block (LBBB), left anterior hemiblock, and left posterior hemiblock[5]. In RBBB, characteristic ECG findings include a wide “rabbit ear” pattern in lead V1 and a wide, slurred S wave in lead V6. Conversely, LBBB typically presents as a wide rS pattern in lead V1 and a broad, notched R wave in lead V6[11].

Additionally, left anterior and posterior hemiblocks refer to specific fascicular blocks within the left bundle branch. Left anterior hemiblock is associated with delayed conduction in the anterior fascicle of the left bundle, while left posterior hemiblock involves delayed conduction in the posterior fascicle. These conditions may be identified through specific ECG criteria and can provide further insight into the underlying cardiac pathology[5,11].

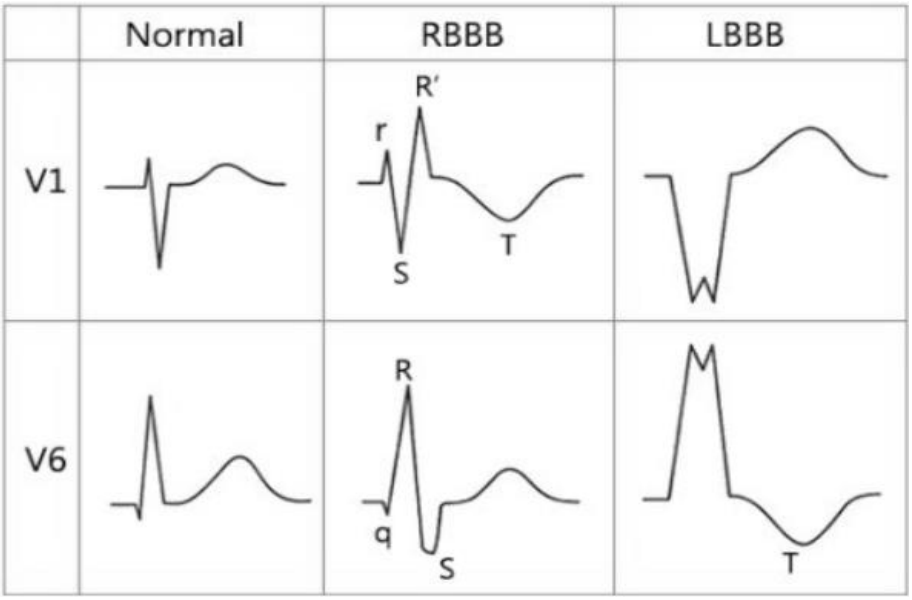


Figure 5. ECG diagrams resulted from bundle branch blocks.

2.2 Cause of disease

From a practical standpoint, the need for temporary cardiac pacing can arise from two distinct categories of conditions: intrinsic and extrinsic factors. Intrinsic conditions typically encompass congenital heart diseases which directly affect the heart's electrical conduction system, leading to bradyarrhythmias necessitating temporary pacing. Conversely, extrinsic factors involve various medical scenarios such as medication usage, postoperative treatments, or the presence of leads causing bradycardia or tachycardia. These external influences can disrupt normal cardiac rhythm, prompting the need for temporary pacing to restore proper heart function. It's crucial for healthcare providers to identify the underlying cause of the bradyarrhythmia to determine the most appropriate management strategy and ensure optimal patient care.

2.2.1 Intrinsic conditions

1) Acute bacterial endocarditis

The emergence of a new conduction system abnormality often indicates the presence of a perivalvular abscess extending to involve the conduction system near the AV node and/or the HIS bundle. Notably, endocarditis primarily affects the non-coronary cusp of the aortic valve, with studies indicating that approximately 15% of patients with aortic valve endocarditis develop third-degree or complete heart block[12].

2) Tumors

Tumors in the head or neck region or around the carotid sinus may lead to high-grade AV block, warranting temporary cardiac pacing as a therapeutic intervention. Lyme disease, a tick-borne

infection, can result in cardiac involvement[13], typically manifesting as AV block, which tends to be transient and often fluctuates between first-degree and higher degrees. While temporary pacing may be required initially, the conduction disturbances frequently resolve with antibiotic treatment.

3) Viral myocarditis and other tick-borne infections

Myocarditis and other tick-borne infections can also cause similar conduction disturbances, occasionally necessitating temporary pacing. In rare cases, metabolic derangements such as acidosis and hyperkalemia may lead to bradycardia requiring temporary pacing until correction of the underlying metabolic abnormalities. Hypothyroidism-related bradycardia rarely requires pacing unless concomitant QT prolongation predisposes to torsade de pointes ventricular tachycardia[14].

4) Motor vehicle accidents and Chagas disease

Cardiac trauma resulting from motor vehicle accidents and Chagas disease, prevalent in Central and South America and caused by Trypanosoma cruzi, can induce bundle branch block or complete heart block, often leading to a cardiomyopathic state[1].

5) Myocarditis of infectious etiology

While relatively uncommon, myocarditis of infectious etiology can also lead to conduction system abnormalities, necessitating temporary cardiac pacing as part of the management strategy[15].

2.2.2 Extrinsic conditions

2.2.2.1 Reversible bradycardia

Immediate and reversible causes such as myocardial ischemia, myocarditis, electrolyte disturbances, toxic exposure, or cardiac surgery induce bradycardia.

1) Drug-induced bradycardia

Several medications may produce transient bradycardia that may require temporary pacing until the effect of the drugs dissipates as they might cause SA node dysfunction or AV node block[5]. Bradycardia induced by drugs is frequently encountered as both an unintended consequence and a beneficial outcome of medical interventions. Even digitalis, beta blockers and calcium channel antagonists, which are commonly used to control the ventricular response during atrial flutter and fibrillation, or in the treatment of coexisting cardiac conductions (e.g., angina and congestive heart failure) can induce bradycardia. If drugs are used in combination, their effects may become more potent and exacerbate mild or latent conduction system disease[5]. It's crucial to consider drug interactions, especially in patients using multiple medications as those drugs can be potential causes of bradycardia whether patients use them for cardiac or non-cardiac treatment[16].

2) Post-operative treatment

2-1) Acute myocardial infarction

Patients with acute myocardial infarction (MI) could suffer from significant bradycardia due to damage of the conduction system by ischemia and/or reperfusion[17]. The right coronary artery supplies SA node in 60%, AV node and His bundle in 90% of patients[18,19]. AV node block is located above the His bundle in most patients with inferior infarction but is usually infra-Hisian and preceded by intraventricular conduction disturbances in anterior infarction[18,20–24]. The incidence of high-degree AV node block in patients with ST-segment elevation MI has declined to 3-4% in the

primary percutaneous coronary intervention era[25–27]. High-degree AV node block is most frequent in inferior or inferolateral infarctions[22,25–28]. Patients with high-degree AV node block have higher clinical risk and larger infarctions especially when AV node block complicates an anterior infarction[25–27,29,30]. New-onset intraventricular conduction disturbance is also associated with larger infarctions[31–34]. AV node block may require temporary pacing in the presence of refractory symptoms or hemodynamic compromise[35].

2-2) Coronary artery bypass graft and Valve surgery

AV block may occur in 1~4% of cases after cardiac surgery, while it's observed in roughly 8% after repeat valve surgery[36–40]. The SA node dysfunction may occur after procedure like right lateral atriotomy or transseptal superior approaches to the mitral valve[37,38]. In clinical practice, a monitoring period of 3-7 days is usually applied before implanting a permanent pacemaker to allow regression of transient bradycardias[37]. In the case of complete AV node block occurring within the first 24 hours after valvular surgery and persisting for 48 hours, resolution within the next 1-2 weeks is unlikely and earlier implantation of pacemaker would be considered[41,42]. During observed period, temporary pacemaker procedure may be necessary[43].

2-3) Heart transplantation

The SA node dysfunction is common and leads to permanent pacemaker implantation after heart transplantation in 8% of patients[37]. Possible causes of SA node dysfunction include surgical trauma, sinus node artery damage, or ischemia and prolonged cardiac ischemic times[44,45]. AV node block is less common and is probably related to inadequate preservation of the donor heart[37,45,46]. As SA node and AV node function improve during the first few weeks after transplantation, an observation period before pacemaker implantation may allow spontaneous improvement of bradycardia[47].

2-4) Transcatheter aortic valve implantation

Rates of permanent pacemaker implantation after transcatheter aortic valve implantation (TAVI) range between 3.4% and 25.9% in randomized trials and large registries[48–60]. For post-TAVI management, temporary cardiac pacing for 24-48 hours is required through monitoring whether pace becomes stable or occurs high-degree AV block[17]. Given the close anatomical proximity of the aortic valve and the left bundle branch, the most frequent conduction abnormality after TAVI is left bundle branch block and temporary pacing can be adapted to treat it[61].

2-5) Post-operative AV block

Post-operative high-degree AV node block occurs in 1-3% of patients undergoing surgery[62,63]. In children, transient early post-operative AV node block usually resolves within 7-10 days[64].

2-6) Temporary pacing prior to non-cardiac surgery

Several studies have suggested a low incidence of intraoperative and perioperative complete heart block. Even in patients with first-degree AV block and bi-fascicular block, there is a very low incidence of perioperative high-grade heart block. However, in patients who have bi-fascicular block and type II second-degree AV block is higher, and temporary pacing is warranted[5].

2.2.2.2 Irreversible bradycardia

Temporary cardiac pacemaker can operate as bridge stage for permanent pacemaker, lead revision or pacemaker generator replacement procedure. Patients who are pacemaker-dependent when a pacemaker generator change, or lead revision/replacement might also require temporary cardiac pacing.

2.2.2.3 Anti-tachycardia Pacing

Rapid temporary cardiac pacing can be used in some situations to prevent a tachyarrhythmia from occurring. An example is torsade de pointes (TdP), a polymorphic ventricular tachycardia associated with a long QT interval. Atrial or ventricular pacing at rates between 90 and 110 BPM can prevent initiation of TdP by shortening the QT interval and by preventing PVCs that might trigger the tachycardia. This approach is not commonly used but may be effective for some patients[1].

CHAPTER 3: Temporary Cardiac Pacemaker

3.1 History of temporary pacemakers

3.1.1 First successful application

In 1952, Paul Zoll first applied clinically effective temporary cardiac pacing using a pulsating current applied through two electrodes attached via hypodermic needles to the chest wall[65]. He paced two patients with ventricular standstill in this transcutaneous manner. Although this technique was uncomfortable for the patients it was effective for 25 minutes in one patient and even five days for the other patient. After this first application, transcutaneous cardiac pacing had become commercially available in the early 1980s[66]. It works by delivering electrical impulses through pads on the patient's chest stimulating the heart muscle for heart contractions and steady heart rate[2]. Transcutaneous pacing is particularly well suited for emergency use and for prophylactic use in situations of life-threatening bradyarrhythmia, which require prompt and certain electrical stimulations for cardiac resuscitation[67].

Though surgeons could effectively apply transcutaneous pacing for emergencies, transcutaneous pacing can be limited by high capture thresholds and patient discomfort, which might require sedation[68]. Because prolonged use of transcutaneous pacing may be unreliable and poorly tolerated, it should generally serve as a short-term bridge to temporary or permanent transvenous pacing or resolution of bradycardia under close hemodynamic monitoring[69].

3.1.2 Emergence of pacing technologies

In order to overcome limitations of external heart stimulations through skin electrodes, researchers had tried to develop more reliable temporary cardiac pacing methods. C. Walton Lillehei introduced myocardial electrodes for the clinical management of acute postoperative heart block at the University of Minnesota Medical Center in January, 1957[70]. After the first medical application, he employed direct stimulations of the ventricular myocardium to 174 patients who suffer from postoperative complete heart block, resulting in reversion to the normal sinus rhythm among 42 percent of them[71].

Temporary cardiac pacing with epicardial pacing wires is used exclusively following cardiac surgery and can be used for temporary cardiac pacing if bradycardia occurs, or for overdrive pacing of postoperative tachyarrhythmias[72]. Leads may be attached to the atrium, ventricle, or both chambers at the time of the cardiac surgical procedure, with the wires tunneled and externalized[72]. There are some cases requiring epicardial methods only.

One of the cases is pacing for infants or children around 15–20 kg, who have such small size of venous that cannot implant pacing catheters endocardial manner[73]. Researchers reported that individually optimized temporary pacing leading were successfully improved hemodynamics in patients with heart failure and dysrhythmias after congenital heart surgery[74]. Also, during postoperative recovery time, some reports demonstrate that temporary pacing may be necessary for almost 50% of patients. Temporary epicardial pacing wires are often placed during cardiopulmonary bypass or valve surgery and performed at the end of heart surgery[39]. Atrial pacing wires, if needed, are sutured to the right body of the atrium or to the right appendage. The wires are passed to the body surface percutaneously. Ventricular pacing wires are inserted on the anterior or diaphragmatic surface[75].

In 1958, Seymour Furman and John Schwedel were able to provide endocardial stimulation by utilizing a lead inserted through the internal jugular vein[76]. Since then, temporary transvenous pacing became one of the most reliable and frequently used types of temporary pacing. Through 60 years of history, temporary transvenous pacing has provided temporary ventricular rate support and thus cardiac output, for patients suffering from severe or clinically significant episodes of

bradycardia or high-grade heart block and asystole due to multiple causes including acute myocardial infarction[2]. This pacing technique contributed to temporary pacemakers have become more common procedures in emergency departments and intensive care unit procedures.

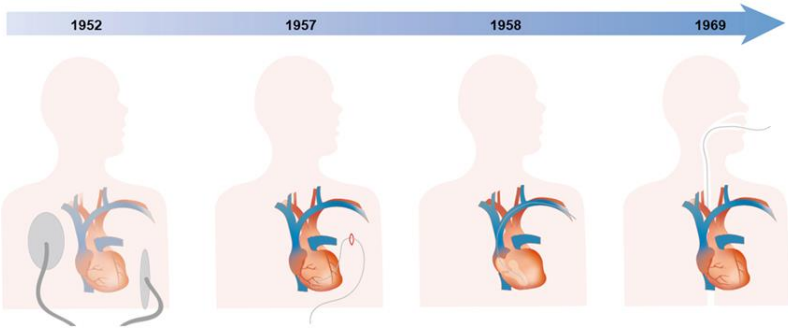
Transvenous pacing is achieved by puncture of the femoral, jugular, brachial, or subclavian vein. Each venous access has advantages and disadvantages. The optimal site depends on the time needed for lead placement. In an emergency, the vein with the easiest access should be preferred. Implantation of a pacing lead via the femoral vein has the disadvantage that the patient remains immobile. However, the access is easy and without major complications. Venous access via the subclavian vein can induce a pneumothorax and should be the second choice. The patient's coagulation status also plays an important role[65].

Unlike permanent cardiac pacing, where the use of a dual-chamber pacemaker is prioritized for the atrioventricular (AV) synchronization, increasing the number of inserted leads can pose a risk in temporary pacing. Generally, if pacing of the ventricle is effectively achieved, adequate temporary cardiac pacing occurs more often with single chamber pacing. Since the need for temporary pacing is often brief, these patients can typically be stabilized with ventricular pacing alone but, rarely, dual-chamber pacing is required[65]. Both unipolar and bipolar pacing wires are available. Using bipolar pacing wires, better sensing and pacing thresholds may sometimes be achieved when compared with unipolar leads. However, bipolar pacing is often more time-consuming[65].

This perivenous placement of an endocardial electrode by cardiac catheterization with an attached external pulse generator is now the most widely used method of providing temporary cardiac stimulation. However, transvenous pacing could be slow and uncertain for the emergency phase of cardiac resuscitation. The risk of displacement makes it unreliable in crucial emergency situations. And the often-time-consuming technique constitutes a significant burden for seriously ill patients[77]. Although these temporary pacing wires are helpful in the management of some patients, they are not without risks in a small number, ranging from simply nonfunctioning wires to life-threating bleeding at the time of removal, and other risks such as infection and discomfort if retained inside the body[78].

Shafiroff and Linder' were the first to demonstrate that the human heart can be paced from the esophagus, and Burack and Furman demonstrated the advantages of this method in emergency

pacing in 1969[79]. Because of the proximity of the esophagus and left atrium, a transesophageal pacemaker lead can be used for atrial pacing the lead requires placement through the nose or mouth[80]. Since contact in the esophagus can be variable, capture consistency is not reliable and high current and broad pulse widths are required, which can be painful. These are uncommonly used in the adult population[81].



Methods	Transcutaneous	Epicardial	Transvenous	Transesophageal
Occasions	Perioperative cardiac management, Emergency	Postoperative cardiac management, Children	Acute reversible bradycardia treatment	Emergent atrial pacing

Figure 6. History and indications for different types of temporary cardiac pacing

3.2 Structure and materials

Temporary pacing systems include an external generator connected to one or two pacing leads, which can be placed either epicardial or transvenous depending on the clinical situation. The external generator, often referred to as a temporary pacemaker unit, serves as the control center for delivering electrical stimuli to the heart. This generator is equipped with advanced electronics and programming capabilities to ensure precise pacing parameters tailored to each patient's specific needs. In addition to the external generator, temporary pacing systems include one or two transcutaneous pacing leads, which serve as conduits for delivering electrical impulses from the generator to the myocardium. These pacing leads are slender, flexible wires with specialized electrodes at their distal ends, designed to make direct contact with the cardiac tissue. The leads are typically made of biocompatible materials such as silicone or polyurethane to minimize the risk of tissue irritation or inflammatory response.

3.2.1 Tips

1) Bare & Balloon tip

Transvenous pacing leads are typically stiffer than permanent pacing leads, making manipulation more difficult, but the leads are balloon-tipped for easier insertion[2]. They come with various curves, including a preformed atrial "J" wire[1]. Use of semirigid fixed curve catheters were associated with high complication rates, particularly in the acute MI setting and when placed by less-experienced operators. A lot of research show faster placement and lower complication rates with balloon-tipped catheters[82,83].

2) Permanent pacemaker lead tip

For some cases, temporary cardiac pacing utilizes same catheters with permanent pacing. Though there are two kinds of fixation method for permanent pacing lead, in a review article, passive fixation leads induced lots of complications including the failure of venous access (15%), failure to place a lead (10%), and sepsis (9%)[78]. Hyman et al. studied 1,022 patients at the Mayo Clinic who required conventional temporary pacing. Lead dislodgement occurred in 17.9% of patients and was the most common complication observed. The overall mortality rate was reported to be 17.6% and another single-center retrospective study with 530 cases described a dislodgement rate of 9%, with 8.8% of deaths[84]. Therefore, active fixation permanent pacing leads are preferred than passive forms. Such temporary permanent pacemakers are placed using active fixation leads, where the tip of the lead is screwed into the myocardium, giving it significantly more stability[85,86]. Venous access can be obtained from the internal jugular or the subclavian vein but not usually via the femoral vein. This provides ease of mobility to the patient and decreases the requirement of ICU-level nursing and monitoring. Use of an active fixation permanent pacing lead externalized and connected to a reusable generator has been introduced as a means of allowing more prolonged temporary pacing for pacemaker-dependent patients who have a contraindication to PPM implantation, such as infection[2].

3.2.2 Materials[87]

Most conductors in temporary pacing leads are constituted with stainless steels due to their hemocompatibility properties. A stainless steel-silver composite wire, called drawn-braze-strand, was introduced in the 1960s. This wire had excellent fatigue. Tinsel wire conductors (metal ribbons wound around a polymer fiber core) were tried in some early leads.

The earliest lead wires used Teflon or polyethylene insulation. These materials were soon replaced by silicone rubber. Silicone is nontoxic, relatively (chemically) inert, and biostable (at least for 10 to 12 years implant as a lead). On the other hand, it has relatively low elastic modulus. Thus, the torsional and flexural properties that affect lead handling characteristics are determined primarily by the properties of the conductor. In addition, silicone rubber has relatively low tensile strength,

elongation, and tear strength. In order to assure a low failure rate (due to cutting, cold flow, wear, etc.), silicone rubber insulation needs to be relatively thick. Because silicone rubber has a high coefficient of friction in blood, considerable drag can occur if two large diameter leads are placed in one vein for dual chamber pacing. Tough silicones were introduced in the early 1980s only partially resolved these deficiencies by improving tensile elongation and tear strength. An alternative insulating material, polyether polyurethane, was introduced by Stokes in 1979. The polyurethanes used today have a significantly higher elastic modulus than silicone, and thus offer more opportunity to affect handling properties of the lead through modification of insulation and conductor design. In addition, these polymers have much higher tensile strength, elongation, and tear strength than silicone, allowing insulation to be thinner without compromising safety. Polyurethane also has a low coefficient of friction in blood.

3.3. Market Outlook[88]

Increasing financial support from government and private entities for the healthcare sector, the rising incidence of cardiovascular diseases, and the demand for minimally invasive procedure are driving market growth. The market is expected to grow from US $ 322.5 million in 2023 to US $ 587.2 million by 2033.

3.3.1. Growth in Minimally Invasive Procedures

The increasing adoption of minimally invasive techniques is becoming integral to cardiac surgery, creating significant opportunities for treating cardiovascular disease. This trend is expected to boost the temporary pacing lead market.

3.3.2. Expanding Elderly Population

The global rise in the elderly population, who are more prone to cardiovascular disease, is expected to increase the demand for surgeries, thereby driving the need for temporary pacing leads. Additionally, the growing requirement for pacing in elderly patients undergoing surgery, coupled with increased life expectancies, presents substantial opportunities for manufacturers in the temporary pacing leads market.

3.3.3. Technological Advancements in Temporary Pacing

The technology and procedure for temporary cardiac pacing have seen significant developments. The introduction of innovative products for temporary pacing has created numerous opportunities in the market.

CHAPTER 4: Complications

Temporary cardiac pacing, a medical intervention with a history spanning approximately 70 years, remains associated with notable risks despite advancements in technology and clinical practice. A study conducted using the US National Inpatient Sample investigated complications and outcomes in a cohort of 360,223 individuals who underwent transvenous temporary pacemaker procedures between 2004 and 2014[89]. The findings underscored the gravity of these procedures, revealing an in-hospital mortality rate of 14.1% within this cohort. Furthermore, the study reported a permanent pacemaker implantation rate of 37.9%, along with incidences of pericardial tamponade (0.6%), pneumothorax (0.9%), and non-pericardial tamponade (2.4%). Notably, manipulation of the pacing lead during catheterization of the right side of the heart may induce transient right bundle branch block in up to 10% of patients, while trauma induced by right ventricle endomyocardial biopsy can lead to temporary or, rarely, long-lasting bundle branch block[5].

The evolution of permanent pacemakers towards leadless designs has mitigated certain risks associated with traditional lead-based systems. However, even in permanent pacemakers utilizing leads, issues related to lead performance and longevity persist, albeit to a lesser extent than in temporary pacing systems. Conversely, in temporary cardiac pacemakers, the presence of pacing leads remains the primary source of complications, manifesting during implantation, operation, and extraction procedures of temporary pacing leads. These complications underscore the importance of ongoing research and innovation aimed at enhancing the safety and efficacy of temporary cardiac pacing technologies.

4.1. Implantation

During the implantation surgery of temporary cardiac pacemakers, several potential complications may arise, necessitating careful consideration and management by the medical team. One such complication is the rare occurrence of vein stenosis, which can result from the insertion of pacing leads into the patient's body. Vein stenosis refers to the narrowing of veins, which can impede blood flow and potentially lead to complications such as pulmonary vein stenosis. Pulmonary veins

play a crucial role in returning oxygen-rich blood from the lungs to the heart, and any constriction or narrowing in these vessels can disrupt normal cardiac function.

Additionally, the insertion of pacing leads during pacemaker implantation surgery carries a risk of bleeding, which can lead to the formation of hematomas[90]. Hematomas occur when blood accumulates outside of blood vessels, forming a localized swelling or mass. While small hematomas may resolve on their own, larger hematomas can exert pressure on surrounding tissues and organs, potentially causing pain, discomfort, or impaired function. In some cases, hematomas may require drainage or surgical intervention to prevent complications such as infection or tissue damage.

Furthermore, the process of inserting pacing leads into the heart chambers carries a risk of perforation or injury to surrounding structures. Perforation can occur if the pacing lead inadvertently punctures the myocardium or adjacent blood vessels, leading to bleeding or leakage of blood into the surrounding tissues. In severe cases, cardiac perforation can result in cardiac tamponade, a life-threatening condition characterized by the accumulation of fluid within the pericardial sac, compressing the heart and impairing its function.

Infection is another potential complication associated with the implantation of temporary cardiac pacemakers. The insertion of foreign objects into the body, such as pacing leads, creates a pathway for bacteria to enter the bloodstream, increasing the risk of infection. Infections can manifest as local site infections at the insertion site or systemic infections such as bacteremia or endocarditis. Prompt identification and treatment of infections are essential to prevent complications and minimize the risk of sepsis or other serious consequences.

Other less common complications of temporary pacemaker implantation surgery include lead dislodgement, device malfunction, allergic reactions to implant materials, and arrhythmias. Lead dislodgement occurs when the pacing lead becomes detached from the myocardium or dislodged from its intended position, compromising pacing function. Device malfunction can occur due to technical issues with the pacing generator or leads, necessitating device replacement or reprogramming. Allergic reactions to implant materials may manifest as localized inflammation or systemic hypersensitivity reactions, requiring appropriate management.

4.2. Lead Positioning

During the operation period of temporary cardiac pacemakers, patients are at risk of experiencing various complications that require close monitoring and management by healthcare providers[84,89–92]. One significant complication is the potential for accidental lead disconnection, particularly in cases where the patient's movements may inadvertently disrupt the positioning or stability of the pacing leads. Lead disconnection can compromise the effectiveness of pacing therapy, leading to inadequate cardiac support and potential hemodynamic instability.

In addition, there is a notable concern for the development of serious infections associated with the percutaneous holes created in the patient's body during the insertion of pacing leads. These percutaneous holes serve as entry points for bacteria, increasing the risk of infection at the insertion site or the surrounding tissues. Infections can range from superficial wound infections to more severe complications such as cellulitis, abscess formation, or bloodstream infections. Preventing infections during the operation period of temporary cardiac pacemakers requires meticulous attention to sterile technique and infection control practices. In some cases, antibiotics may be prescribed prophylactically to reduce the risk of infection, particularly in patients with underlying comorbidities or immunocompromised states.

4.3. Extraction

During the extraction surgery of temporary cardiac pacemakers, both transvenous and epicardial pacing systems may encounter various complications that require careful management by healthcare providers[93,94]. One significant complication is wire entrapment, which can occur during the removal of pacing leads. Wire entrapment refers to the unintentional entanglement or trapping of pacing leads within the vasculature or cardiac tissues, posing challenges for safe and successful lead extraction.

Additionally, the extraction of temporary pacing leads can sometimes lead to the development of arrhythmias, particularly micro shock-induced arrhythmias. Micro shock refers to

the unintended delivery of small electrical currents during lead manipulation or removal, which can trigger arrhythmic events such as atrial or ventricular fibrillation. Healthcare providers must exercise caution and employ appropriate techniques to minimize the risk of micro shock-induced arrhythmias during lead extraction procedures.

Cardiac perforations and bleeding are also potential complications associated with the extraction of temporary pacing systems. The manipulation of pacing leads within the cardiac chambers or epicardial space can inadvertently lead to perforations of the myocardium or surrounding blood vessels, resulting in bleeding and potential hemodynamic instability. Prompt identification and management of cardiac perforations and bleeding are essential to prevent complications such as cardiac tamponade or exsanguination.

In the case of epicardial pacing lead extraction, there are additional risks associated with fibrotic tissue growth on the epicardial surface. Over time, the presence of pacing leads can stimulate the formation of fibrotic tissue around the leads, creating a fibrin tissue sheath that encases the leads and makes extraction more challenging. Prolonged pacing may exacerbate this fibrotic response, further complicating lead removal and increasing the risk of tissue damage or perforation.

Furthermore, mechanical irritation of the epicardium during lead extraction procedures can precipitate the generation of arrhythmias such as atrial or ventricular fibrillation. Healthcare providers must carefully assess the patient's cardiac rhythm and stability throughout the extraction process and be prepared to intervene promptly in the event of arrhythmic complications.

In some cases, despite attempts at lead extraction, the distal tip of the pacing lead may remain lodged in the vein, necessitating additional open-heart surgery for retrieval. This scenario underscores the importance of thorough preoperative planning, meticulous technique, and close postoperative monitoring to minimize the risk of incomplete lead extraction and associated complications.

Stage	Occasions
Implantation	Vein stenosis, Hematoma
Operation	Lead displacement, Bleeding, Local and systemic infection, Accidental disconnection/fracture of leads
Extraction	Perforation, Bleeding, Cardiac tamponade, Arrhythmia, Pneumothorax

Table 1. Complications during temporary cardiac pacing

CHAPTER 5: Bioresorbable Pacemaker

5.1. Bioresorbable Materials

Based on those advances, Choi et al proposed the first fully implantable and bioresorbable cardiac pacemakers without any leads or batteries, which can be externally controlled and programmable[95]. The device was meticulously crafted using bioresorbable materials, marking a significant advancement in cardiac pacemaker technology.

The schematic illustration in Figure 6a (left) depicts a thin, flexible, leadless cardiac pacemaker delicately positioned on the heart's surface. The wireless power harvesting component, as depicted in Fig. 1a (middle), features a loop antenna boasting a bilayer, dual-coil configuration. This setup includes a tungsten-coated magnesium (W/Mg) layer measuring approximately 700 nm in thickness, coupled with a film of poly(lactide-co-glycolide) (PLGA) 65:35 serving as a dielectric interlayer, approximately 50 μm thick. Additionally, a radiofrequency (RF) PIN diode, crafted from doped monocrystalline silicon nanomembrane (Si NM), approximately 320 nm thick, completes this intricate setup. Electrical interconnections are established using a composite paste comprising Candelilla wax and tungsten (W) micro-particles, ensuring reliable performance. To safeguard the active materials from surrounding biofluids during the implantation period, two layers of PLGA 65:35 encapsulate the entire system. This encapsulation structure, with a thickness of approximately 100 μm, provides robust isolation while maintaining the device's functionality.

A strip of double-layered electrode (W/Mg; ~700 nm / ~50 μm thick), with an aperture at one end, functions as both an electrical extension and connector. This innovative design facilitates the delivery of electrical stimuli from the receiver (Rx) antenna to the myocardium. Notably, the W/Mg electrode design is compatible with computed tomography (CT), enabling non-invasive monitoring of the bioresorption process. The exposed pair of electrodes, measuring 2.0 × 1.4 mm^2, features adjacent holes (700 μm diameter) utilized for suturing to the heart using bioresorbable suture material. Remarkably, the geometry of the entire system is characterized by its compactness, thinness, and lightweight construction. With a volume of approximately 0.05 cc, a width of around 16 mm, a length exceeding 15 mm, and a thickness of approximately 250 μm, the device offers a

blend of efficiency and unobtrusiveness. Moreover, weighing merely 0.3 g, it ensures minimal interference with the natural dynamics of the heart.

The key defining characteristic of this system is the bioresorbable nature of all its constituent materials. These designs ensure stable functionality over a pertinent timeframe, culminating in their complete dissolution within the surrounding biofluids and eventual absorption by the body itself, facilitated by natural chemical and biochemical processes such as hydrolysis and metabolic action (see Figure 6a, right). For example, PLGA undergoes hydrolysis to its monomers, glycolic and lactic acid[96], while the Mg, Si NM and W transform into non-toxic products, according to ($Mg + 2H_2O \rightarrow Mg(OH)_2 + H_2$), ($Si + 4H_2O \rightarrow Si(OH)_4 + 2H_2$), and ($2W + 2H_2O + 3O_2 \rightarrow 2H_2WO_4$), respectively[95,97]. The incorporation of Candelilla wax, with its composition of long-chain poly- and mono-unsaturated esters, fatty acids, anhydrides, short-chain hydrocarbons, and resins, ensures its gradual hydrolysis and subsequent absorption into the body[95]. Photographic evidence presented in Figure 6b depicts a typical device at various intervals following immersion in a phosphate-buffered saline (PBS, pH 7.4; 37°C). Remarkably, these constituent materials exhibit significant dissolution within five weeks, with any residual traces completely disappearing after seven weeks.

Moreover, the heart's intrinsic curved structure and rhythmic deformation patterns underscore the importance of employing soft and flexible devices[98]. This characteristic presents a promising alternative to the mechanically rigid cardiac pacemakers typically used. Through meticulous design considerations and mechanical analyses, it has been determined that the maximum strains experienced by the magnesium electrodes and PLGA encapsulation remain below 0.6% during a compression of 20%, indicative of their linear elastic behavior. Such inherent mechanical flexibility enables the placement of a bioresorbable cardiac pacemaker on the epicardium, ensuring optimal performance and compatibility with the dynamic nature of the heart.

5.2. Leadless and Battery-free Pacing

The device's wireless operation and pacing functionality have been successfully validated through in vivo experiments conducted on rodent and canine models[99]. Although the application evaluated in this series of experiments primarily addresses the need for temporary leadless epicardial pacing, still, require external, wall-plugged equipment for monitoring, power, and control. This bioresorbable pacemaker also have a limitation, which can only operate less than 4 days due to its inadequate water barrier properties.

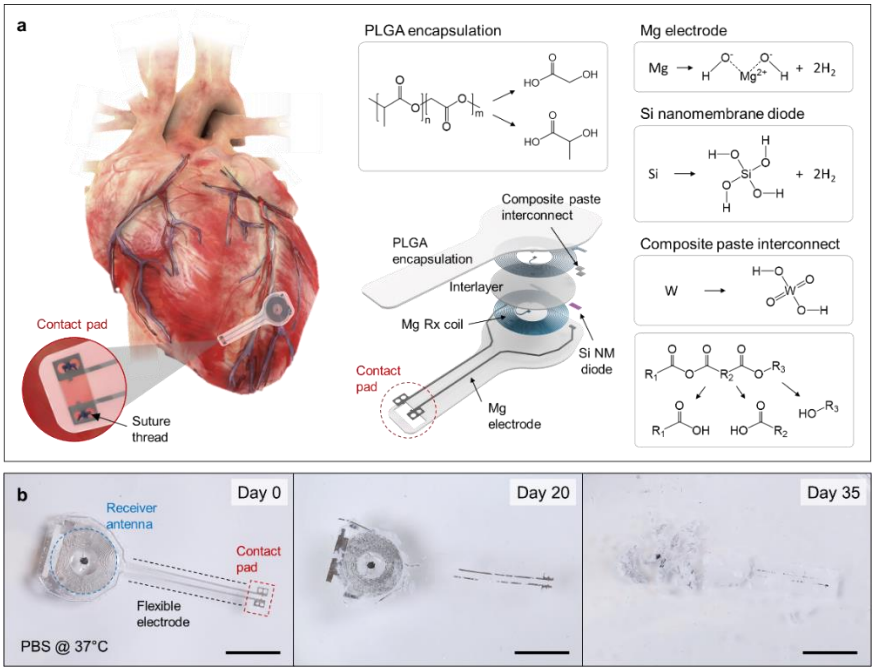


Figure 7. Materials, design and proposed utilization of a bioresorbable, implantable, leadless, battery-free cardiac pacemaker. (a) Schematic illustration of the device mounted on the myocardial tissue, design of the device, and chemical reaction for the hydrolysis of constituent materials. (b) Images of dissolution of a device associated with immersion in PBS (pH 7.4; 37°C). Scale bar, 10 mm[95].

5.3. Closed-loop System

Choi et al developed transient closed-loop systems which enables dehospitalization of patients integrating their novel polymer named ‘b-DCPU’, which minimize swelling through its property of dynamic covalent bonds leading to robust operations in the body (Figure 7.)[100]. This transient, closed-loop system represents a distributed, wireless bioelectronics technology that provides autonomous electrotherapy over a time frame that matches postoperative needs. The operation involves coordinated operation of a network of skin-interfaced modules and a bioresorbable device in time-synchronized communication with a control platform. Data captured from various locations of the body yield detailed information on cardiopulmonary health and physical activity. The results define autonomous, rate-adaptive pacing parameters to match metabolic demand through wireless powering of the bioresorbable module; they also support feedback on device and physiological status through a multihaptic interface. The bioresorbable module for cardiac pacing undergoes complete dissolution by natural biological processes after a defined operating time frame. The skin-interfaced devices can be easily removed after patient recovery. This system provides a framework for closed-loop technologies to treat various diseases and temporary patient conditions in a way that can complement traditional biomedical devices and pharmacological approaches.

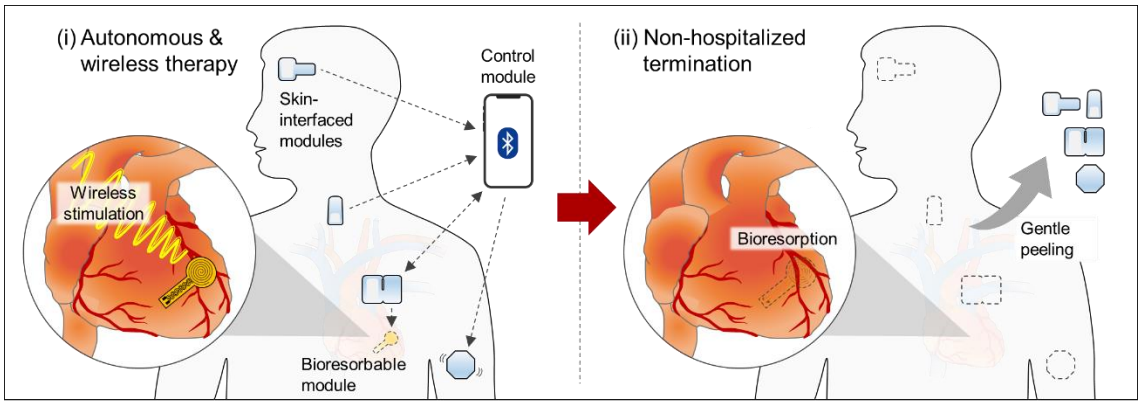


Figure 8. A transient closed-loop system with bioresorbable cardiac pacemaker[100].

CHAPTER 6: Conclusion

Bradycardia, a condition characterized by an abnormally slow heart rate, can lead to serious health issue. Traditional temporary pacemakers involve lead insertion through endocardial access, which carries a lower risk of complications but might be led to additional surgical intervention for lead removal. In contrast bioresorbable temporary cardiac pacemakers have revolutionized temporary cardiac pacing by enabling lead removal and empowering patients with self-monitoring capabilities. Bioresorbable pacemakers address this issue by naturally dissolving within the body, eliminating the need for additional surgeries and significantly reducing associated risks.

However, there is still room for advancement. Presently, bioresorbable pacemaker can only operate single chamber epicardial pacing, which is capable of ventricular pacing only. These devices are limited to single chamber epicardial approaches, whereas the more commonly used endocardial access remains unexplored. In temporary pacing, though rare, also there are cases where dual chamber pacing is necessary for atrial-ventricle synchronization, or situations where only atrial pacing is required. Therefore, there is still a demand for the development of pacemakers that can deal with all medical situations. Also, expanding to endocardial access via a sheath could enhance performance and cater to the growing temporary pacemaker market.

Though b-DCPU-based pacemaker could achieve in vivo functional lifetime of over a month based on remarkable mechanical stretchability (>200% of elongation) and robust in-plane encapsulation through dynamic covalent bonding, limitations still exist in our inability to actively control the timing of device removal. Concerns also arise because the intended pacing may not occur properly during the dissolving period of the device when relatively longer-term pacing is required. In demands of controllable degradation, researchers have been developed polymers their degradation can be triggered by biological product[101]. Introduction of such materials would bring a new device technology, where patients can flexibly control the lifetime of pacemaker.

References

1. N. A. Mark Estes III. Temporary cardiac pacing. *UpToDate* Wolters Kluwer (2024).
2. Kusumoto, F. M. *et al.* 2018 ACC/AHA/HRS guideline on the evaluation and management of patients with bradycardia and cardiac conduction delay: A report of the american college of cardiology/american heart association task force on clinical practice guidelines and the heart rhythm society. *Circulation* **140**, e382–e482 (2019).
3. Egas, D. *et al.* Burden of bradycardia and barriers to accessing bradycardia therapy in underserved countries. *European Heart Journal, Supplement* **25**, H1–H7 (2023).
4. Conor Stewart. Number of new pacemaker implants in Sweden in 2021, by gender and age. https://www.statista.com/statistics/982602/number-of-pacemaker-implants-in-sweden-by-region/ (2023).
5. Ellenbogen, Kenneth A. & Karoly Kaszala. *Cardiac Pacing and ICDs*. (John Wiley & Sons, 2014).
6. Cleveland clinic. Heart conduction system (cardiac conduction). https://my.clevelandclinic.org/health/body/21648-heart-conduction-system (2021).
7. Edwards, S. J., Karner, C., Trevor, N., Wakefield, V. & Salih, F. Dual-chamber pacemakers for treating symptomatic bradycardia due to sick sinus syndrome without atrioventricular block: A systematic review and economic evaluation. *Health Technol Assess (Rockv)* **19**, 1–210 (2015).
8. Camm, A. J., Thomas F. Luscher & Patrick W. Serruys. *The ESC Textbook of Cardiovascular Medicine*. (Oxford University Press, 2019).
9. George Katritsis, Vishal Luther, Prapa Kanagaratnam & Nick Wf Linton. Arrhythmia mechanisms revealed by ripple mapping. *Arrhythmia Electrophysiology Review* **7**, 261–264 (2018).
10. Anderson, R. H., Mori, S., Spicer, D. E., Sanchez-Quintana, D. & Jensen, B. The anatomy, development, and evolution of the atrioventricular conduction axis. *J Cardiovasc Dev Dis* **5**, 44 (2018).

11. Weston T. Harkness; Mary Hicks. *Right Branch Bundle Block*. *StatPearls* (StatPearls Publishing, 2023).
12. Graupner, C. *et al.* Periannular extension of infective endocarditis. *J Am Coll Cardiol* **39**, 1204–1211 (2002).
13. Yeung, C. & Baranchuk, A. Diagnosis and treatment of lyme carditis: JACC review topic of the week. *J Am Coll Cardiol* **73**, 717–726 (2019).
14. Sozzi, F. B. *et al.* Viral myocarditis: Classification, diagnosis, and clinical implications. *Front Cardiovasc Med* **9**, 908663 (2022).
15. Brociek, E. *et al.* Myocarditis: Etiology, pathogenesis, and their implications in clinical practice. *Biology (Basel)* **12**, 874 (2023).
16. Devamsh, G. N., Patil, M. & Shafiq, S. Drug-induced bradycardia. *Clinical Medicine, Journal of the Royal College of Physicians of London* **23**, 173–174 (2023).
17. Glikson, M. *et al.* 2021 ESC guidelines on cardiac pacing and cardiac resynchronization therapy. *Eur Heart J* **42**, 3427–3520 (2021).
18. Zimetbaum, P. J. & Josephson, M. E. Use of the electrocardiogram in acute myocardial infarction. *N Engl J Med* **10**, 933–973 (2003).
19. Pejkovic, B., Krajnc, I., Anderhuber, F. & Košutic, D. K. Anatomical aspects of the arterial blood supply to the sinoatrial and atrioventricular nodes of the human heart. *J Int Med Res* **36**, 691–698 (2008).
20. Ritter, W. S., Atkins, J. M., Blomqvist, C. G. & Mullins, C. B. Permanent pacing in patients with transient trifascicular block during acute myocardial infarction. *Am J Cardiol* **38**, 205–208 (1976).
21. Ginks, W. R., Sutton, R. & Leatham, A. Long-term prognosis after acute anterior infarction with atrioventricular block. *Heart* **39**, 186–189 (1977).
22. Feigl, D., Ashkenazy, J. & Kishon, Y. Early and late atrioventricular block in acute inferior myocardial infarction. *J Am Coll Cardiol* **4**, 35–38 (1984).
23. Jim, M.-H., Chan, A. O., Tse, H.-F., Barold, S. S. & Lau, C.-P. Clinical and angiographic findings of complete atrioventricular block in acute inferior myocardial infarction. *Annals Academy of Medicine Singapore* **39**, 185–190 (2010).

24. Sutton, R. & Davies, M. The conduction system in acute myocardial infarction complicated by heart block. *Circulation* **38**, 987–992 (1968).
25. Gang, U. J. O. *et al.* High-degree atrioventricular block complicating ST-segment elevation myocardial infarction in the era of primary percutaneous coronary intervention. *Europace* **14**, 1639–1645 (2012).
26. Auffret, V. *et al.* High-degree atrioventricular block complicating ST segment elevation myocardial infarction in the contemporary era. *Heart* **102**, 40–49 (2016).
27. Kim, K. H. *et al.* Differential clinical implications of high-degree atrioventricular block complicating ST-segment elevation myocardial infarction according to the location of infarction in the era of primary percutaneous coronary intervention. *Korean Circ J* **46**, 315–323 (2016).
28. Kosmidou, I. *et al.* Incidence, predictors, and outcomes of high-grade atrioventricular block in patients with ST-segment elevation myocardial infarction undergoing primary percutaneous coronary intervention (from the HORIZONS-AMI trial). *Am J Cardiol* **119**, 1295–1301 (2017).
29. Singh, S. M. *et al.* High-grade atrioventricular block in acute coronary syndromes: Insights from the global registry of acute coronary events. *Eur Heart J* **36**, 976–983 (2015).
30. Meine, T. J. *et al.* Incidence, predictors, and outcomes of high-degree atrioventricular block complicating acute myocardial infarction treated with thrombolytic therapy. *Am Heart J* **149**, 670–674 (2005).
31. Hindman, M. C. *et al.* The clinical significance of bundle branch block complicating acute myocardial infarction 1. Clinical characteristics, hospital Mortality, and one-year follow-up. *Circulation* **58**, 679–688 (1978).
32. Melgarejo-Moreno, A. *et al.* Incidence, clinical characteristics, and prognostic significance of right bundle-branch block in acute myocardial infarction. *Circulation* **96**, 1139–1144 (1997).
33. Vivas, D. *et al.* Prognostic implications of bundle branch block in patients undergoing primary coronary angioplasty in the stent era. *Am J Cardiol* **105**, 1276–1283 (2010).
34. Xiong, Y. *et al.* The prognostic significance of right bundle branch block: A meta-analysis of prospective cohort studies. *Clin Cardiol* **38**, 604–613 (2015).

35. Taggart, C., Wereski, R., Mills, N. L. & Chapman, A. R. Diagnosis, investigation and management of patients with acute and chronic myocardial injury. *J Clin Med* **10**, 2331 (2021).
36. Brodell, G. K., Cosgrove, D., Schiavone, W., Underwood, D. A. & Loop, F. D. Cardiac rhythm and conduction disturbances in patients undergoing mitral valve surgery. *Cleve Clin J Med* **58**, 397–399 (1991).
37. Chung, M. K. Cardiac surgery: Postoperative arrhythmias. *Crit Care Med* **28**, 136–144 (2000).
38. Jaeger, F. J., Trohman, R. G., Brener, S. & Loop, F. Permanent pacing following repeat cardiac valve surgery. *Am J Cardiol* **74**, 505–507 (1994).
39. Reade, M. C. Temporary epicardial pacing after cardiac surgery: A practical review part 1: General considerations in the management of epicardial pacing. *Anaesthesia* **62**, 264–271 (2007).
40. Reade, M. C. Temporary epicardial pacing after cardiac surgery: A practical review part 2: Selection of epicardial pacing modes and troubleshooting. *Anaesthesia* **62**, 364–373 (2007).
41. Glikson, M. *et al.* Indications, effectiveness, and long-term dependency in permanent pacing after cardiac surgery. *Am J Cardiol* **80**, 1309–1313 (1997).
42. Kim, M. H. *et al.* Complete atrioventricular block after valvular heart surgery and the timing of pacemaker implantation. *Am J Cardiol* **87**, 649–651 (2001).
43. Peretto, G., Durante, A., Limite, L. R. & Cianflone, D. Postoperative arrhythmias after cardiac surgery: Incidence, risk factors, and therapeutic management. *Cardiol Res Pract* **2014**, 615987 (2014).
44. Dibiase, A., Tse, T.-M., Wexler, L., Stinson, E. B. & Valantine, H. A. Frequency and mechanism of bradycardia in cardiac transplant recipients and need for pacemakers. *Am J Cardiol* **67**, 1385–1389 (1991).
45. Melton, I. C., Gilligan, D. M., Wood, M. A. & Ellenbogen, K. A. Optimal cardiac pacing after heart transplantation. *Pacing and Clinical Electrophysiology* **22**, 1510–1527 (1999).

46. Jacquet, L. *et al.* Cardiac rhythm disturbances early after orthotopic heart transplantation: Prevalence and clinical importance of the observed abnormalities. *J Am Coll Cardiol* **16**, 832–837 (1990).
47. Holt, N. D. & Mccomb, J. M. Cardiac transplantation and Pacemakers: When and what to implant. *Card Electrophysiol Rev* **6**, 140–151 (2002).
48. Leon, M. B. *et al.* Transcatheter aortic-valve implantation for aortic stenosis in patients who cannot undergo surgery. *New England Journal of Medicine* **363**, 1597–1607 (2010).
49. Smith, C. R. *et al.* Transcatheter versus surgical aortic-valve replacement in high-risk patients. *New England Journal of Medicine* **364**, 2187–2198 (2011).
50. Leon, M. B. *et al.* Transcatheter or surgical aortic-valve replacement in intermediate-risk patients. *New England Journal of Medicine* **374**, 1609–1620 (2016).
51. Mack, M. J. *et al.* Transcatheter aortic-valve replacement with a balloon-expandable valve in low-risk patients. *New England Journal of Medicine* **380**, 1695–1705 (2019).
52. Adams, D. H. *et al.* Transcatheter aortic-valve replacement with a self-expanding prosthesis. *New England Journal of Medicine* **370**, 1790–1798 (2014).
53. Popma, J. J. *et al.* Transcatheter aortic-valve replacement with a self-expanding valve in low-risk patients. *New England Journal of Medicine* **380**, 1706–1715 (2019).
54. Reardon, M. J. *et al.* Surgical or transcatheter aortic-valve replacement in intermediate-risk patients. *New England Journal of Medicine* **376**, 1321–1331 (2017).
55. Barbash, I. M. *et al.* Outcomes of patients at estimated low, intermediate, and high risk undergoing transcatheter aortic valve implantation for aortic stenosis. *Am J Cardiol* **116**, 1916–1922 (2015).
56. Bekeredjian, R. *et al.* Patients at low surgical risk as defined by the society of thoracic surgeons score undergoing isolated interventional or surgical aortic valve implantation: in-hospital data and 1-year results from the German Aortic Valve Registry (GARY). *Eur Heart J* **40**, 1323–1330 (2019).
57. Gilard, M. *et al.* Registry of transcatheter aortic-valve implantation in high-risk patients. *New England Journal of Medicine* **366**, 1705–1715 (2012).

58. Moat, N. E. *et al.* Long-term outcomes after transcatheter aortic valve implantation in high-risk patients with severe aortic stenosis: The U.K. TAVI (United Kingdom transcatheter aortic valve implantation) registry. *J Am Coll Cardiol* **58**, 2130–2138 (2011).
59. Thomas, M. *et al.* Thirty-day results of the SAPIEN aortic bioprosthesis european outcome (SOURCE) registry. *Circulation* **122**, 62–69 (2010).
60. Werner, N. *et al.* Patients at intermediate surgical risk undergoing isolated interventional or surgical aortic valve implantation for severe symptomatic aortic valve stenosis. *Circulation* **138**, 2611–2623 (2018).
61. Auffret, V. *et al.* Conduction disturbances after transcatheter aortic valve replacement: Current status and future perspectives. *Circulation* **136**, 1049–1069 (2017).
62. Fraccaro, C. *et al.* Incidence, predictors, and outcome of conduction disorders after transcatheter self-expandable aortic valve implantation. *American Journal of Cardiology* **107**, 747–754 (2011).
63. Gross, G. J., Chiu, C. C., Hamilton, R. M., Kirsh, J. A. & Stephenson, E. A. Natural history of postoperative heart block in congenital heart disease: Implications for pacing intervention. *Heart Rhythm* **3**, 601–604 (2006).
64. Murphy, D. A., Tynan, M., Graham, G. R. & Bonham-Carter, R. E. Prognosis of complete atrioventricular dissociation in children after open-heart surgery. *The Lancet* **1**, 750–752 (1970).
65. Paul M Zoll. Resuscitation of the heart in ventricular standstill by external electric stimulation. *New England Journal of Medicine* **247**, 768–771 (1952).
66. Rami Doukky, Raed Bargout, Russell F Kelly & James E Calvin. Using transcutaneous cardiac pacing to best advantage. *J Crit Illn* **18**, 219–225 (2003).
67. Creedon, Jamie M. Burkitt & Harold Davis. *Advanced Monitoring and Procedures for Small Animal Emergency and Critical Care*. (John Wiley & Sons, 2023).
68. Bektas, F. & Soyuncu, S. The efficacy of transcutaneous cardiac pacing in ED. *American Journal of Emergency Medicine* **34**, 2090–2093 (2016).
69. Quast, A. F. B. E. *et al.* Feasibility of an entirely extracardiac, minimally invasive, temporary pacing system. *Circ Arrhythm Electrophysiol* **12**, e007182 (2019).

70. Weirich W. L., Gott V. L. & Lillehei C. W. The treatment of complete heart block by the combined use of a myocardial electrode and an artificial pacemaker. *Surg Forum* **8**, 360–363 (1957).
71. Lillehei C.W., Levy M. J., Bonnabeau Jr R. C., Long D. M. & Sellers R. D. The use of a myocardial electrode and pacemaker in the management of acute postoperative and postinfarction complete heart block. *Surgery* **56**, 463–472 (1964).
72. Aser, R. *et al.* Temporary epicardial pacemaker wires: Significance of position and electrode type. *Thoracic and Cardiovascular Surgeon* **62**, 66–69 (2014).
73. Baruteau, A. E. *et al.* Congenital and childhood atrioventricular blocks: pathophysiology and contemporary management. *Eur J Pediatr* **175**, 1235–1248 (2016).
74. Janousek, J. *et al.* Hemodynamically optimized temporary cardiac pacing after surgery for congenital heart defects. *Pacing and Clinical Electrophysiology* **23**, 1250–1259 (2000).
75. Nido, P. Del & Goldman, B. S. Temporary epicardial pacing after open heart surgery: complications and prevention. *The Journal of Cardiac Surgery* **4**, 99–103 (1989).
76. Furman S. & Robinson G. The use of an intracardiac pacemaker in the correction of total heart block. *Surg Forum* **9**, 245–248 (1958).
77. Zoll, P. M. *et al.* External noninvasive temporary cardiac pacing: clinical trials. *Circulation* **71**, 937–944 (1985).
78. Jorge López Ayerbe *et al.* Marcapasos temporales: utilización actual y complicaciones. *Rev Esp Cardiol* **57**, 1045–1052 (2004).
79. Burack, B. & Furman, S. Transesophageal cardiac pacing. *Am J Cardiol* **23**, 469–472 (1969).
80. Rivard, L. *et al.* Electrocardiographic and electrophysiological predictors of atrioventricular block after transcatheter aortic valve replacement. *Heart Rhythm* **12**, 321–329 (2015).
81. Andersen, H. R. & Pless, P. Trans-esophageal pacing. *Pacing and Clinical Electrophysiology* **6**, 674–679 (1983).
82. Lang, R. *et al.* The use of the balloon-tipped floating catheter in temporary transvenous cardiac pacing. *Pacing and Clinical Electrophysiology* **4**, 491–495 (1981).

83. Ferguson, J. D., Banning, A. P. & Bashir, Y. Randomised trial of temporary cardiac pacing with semirigid and balloon-flotation electrode catheters Research letters. *The Lancet* **349**, 1883 (1997).

84. Hynes, J. K., David R. Holmes Jr & Carlos E. Harrison. Five-year experience with temporary pacemaker therapy in the coronary care unit. *Mayo Clin Proc* **58**, 122–126 (1983).

85. Suarez, K. & Banchs, J. E. A review of temporary permanent pacemakers and a comparison with conventional temporary pacemakers. *Journal of Innovations in Cardiac Rhythm Management* **0**, 3652–3661 (2019).

86. Guerrero, J. J. G. *et al.* Lower incidence of venous thrombosis with temporary active-fixation lead implantation in mobile patients. *Europace* **12**, 1604–1607 (2010).

87. Kenneth Stokes. Implantable pacing lead technology. *IEEE Engineering in Medicine and Biology Magazine* **9**, 43–49 (1990).

88. Sabyasachi Ghosh. Temporary pacing leads market. https://www.futuremarketinsights.com/reports/temporary-pacing-leads-market# (2023).

89. Metkus, T. S., Schulman, S. P., Marine, J. E. & Eid, S. M. Complications and outcomes of temporary transvenous pacing: An analysis of > 360,000 patients from the national inpatient sample. *Chest* **155**, 749–757 (2019).

90. Tjong, F. V. Y., de Ruijter, U. W., Beurskens, N. E. G. & Knops, R. E. A comprehensive scoping review on transvenous temporary pacing therapy. *Netherlands Heart Journal* **27**, 462–473 (2019).

91. Austin, J. L., Preis, L. K., Crampton, R. S., Beller, G. A. & Martin, R. P. Analysis of pacemaker malfunction and complications of temporary pacing in the coronary care unit. *Am J Cardiol* **49**, 301–306 (1982).

92. Lazarescu, C., Mertes, P. M. & Longrois, D. Temporary epicardial pacing following cardiac surgery: Practical aspects. *Ann Fr Anesth Reanim* **32**, 592–601 (2013).

93. Koulouris, S., Pastromas, S. & Manolis, A. S. Removal of a temporary pacemaker lead fragment with the use of biopsy forceps. *Europace* **11**, 131 (2009).

94. Parizad, R., Khalili, A., Jodati, A., Rahimi, M. & Faravn, A. Incomplete removal and accidental retention of temporary epicardial pacing wires in the chest after heart surgery: A case report. *J Teh Univ Heart Ctr* **16**, 129–131 (2021).
95. Choi, Y. S. *et al.* Fully implantable and bioresorbable cardiac pacemakers without leads or batteries. *Nat Biotechnol* **39**, 1228–1238 (2021).
96. Kang, S. K. *et al.* Bioresorbable silicon electronic sensors for the brain. *Nature* **530**, 71–76 (2016).
97. Yu, K. J. *et al.* Bioresorbable silicon electronics for transient spatiotemporal mapping of electrical activity from the cerebral cortex. *Nat Mater* **15**, 782–791 (2016).
98. AlGhatrif, M. & Lindsay, J. A brief review: history to understand fundamentals of electrocardiography. *J Community Hosp Intern Med Perspect* **2**, 14383 (2012).
99. Lee, J., Park, S. & Choi, Y. Organic encapsulants for bioresorbable medical electronics. *MRS Bull* **49**, 247–255 (2024).
100. Choi, Y. S. *et al.* A transient, closed-loop network of wireless, body-integrated devices for autonomous electrotherapy. *Science* **376**, 1006–1012 (2022).
101. Xu, C., Huang, Y., Wu, J., Tang, L. & Hong, Y. Triggerable degradation of polyurethanes for tissue engineering applications. *ACS Appl Mater Interfaces* **7**, 20377–20388 (2015).

Korean Abstract (국문 요약)

임시형 인공심박동기 현재와 미래

심장의 외벽 혹은 내벽에 부착된 전극선을 통해 전기 자극을 전달함으로써 느려진 심장박동을 조절할 수 있는 페이스메이커는 영구형과 임시형으로 구분된다. 임상적으로 임시형 페이스메이커는 널리 사용되고 있지만, 가역적으로 돌아올 수 있는 서맥이나, 영구형 페이스메이커 삽입 전 단계에서 사용된다는 특징 때문에 몸 안에 삽입되어 반영구적으로 사용하는 영구형 페이스메이커보다는 개발이 더디게 이루어지고 있다. 그럼에도 불구하고 전극선을 삽입하는 과정 중이나 이후에 발생할 수 있는 부작용의 위험성이 여전히 존재하기 때문에 이에 대한 개선점이 필요한 실상이다.

이 논문은 느린 맥이 발생하는 원인을 전기생리학적 관점에서 설명하고, 임시형 페이스메이커는 언제 임상적으로 사용되는지, 심장박동기의 역사와 재료는 어떤 발전과정을 거쳤는지를 다루었으며, 세계적인 시장 규모와 추세 역시 다뤘다. 이후 최근 새롭게 제시된 생체 흡수형 재료와 폐 루프 시스템을 이용한 임시형 페이스메이커를 소개한다. 본 논문의 결론부에서는, 기존 연구에 대한 요약과 함께, 차세대 임시형 심장박동기 개발에 대한 아이디어를 제시하였다.

핵심 되는 말: 페이스메이커, 임시형 페이스메이커, 생체 흡수형 재료, 폐 루프 시스템, 원격진료, 디지털 헬스