Heart Rhythm Services
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Dear Colleagues,

Thank you for your interest in the Division of Heart Rhythm Services, Department of Cardiovascular Medicine, at Mayo Clinic. We appreciate this opportunity to share with you exciting new developments in our heart rhythm practice, as well as our practice volumes and outcomes.

Dedicated heart rhythm research and practice within cardiology at Mayo Clinic has a rich history dating back to 1914 when the first Cambridge ECG device arrived from England. The first surgically implanted pacemakers at Mayo Clinic followed in the 1950s, while the first surgical mapping of an accessory pathway with subsequent lidocaine suppression was performed in 1967. “Heart Rhythm” as a separate clinical section was created in the 1970s, when invasive catheter-based diagnostic electrophysiology studies came of age. The catheter-based direct-current ablations followed in the early 1980s, and the first thoracic ICD implant was performed in 1985. We have had extensive experience with radiofrequency catheter ablation for atrial fibrillation and ventricular tachycardia, and with cardiac pacing resynchronization since the mid-1990s.

Mayo Clinic is a seminal academic medical center on the forefront of both basic and clinical electrophysiology research. Twenty-seven clinical research protocols are currently ongoing, and several of our investigators have active NIH research programs. More than 175 peer-reviewed papers were published by faculty in 2018. In the tradition of the Mayo Clinic model, we have developed integrated research and innovation programs in multiple disciplines, including genomics, regenerative medicine, metabolomics, channelopathies, ablation biophysics, artificial intelligence, virtual and augmented reality, arrhythmia epidemiology, remote monitoring, and health care delivery science. The electrophysiology graduate training programs in Minnesota and Arizona have matriculated over 100 fellows over the past 30 years; the Florida graduate training program begins in 2020.

We currently have 37 active heart rhythm faculty at our six campuses in Arizona, Florida, Minnesota, and Wisconsin. Additionally, a vigorous pediatric electrophysiology program complements our adult program at the Rochester, Minnesota campus. Streamlined clinical arrhythmia diagnostics and therapeutics are included as part of integrated multidisciplinary programs that include complex congenital heart disease, inherited channelopathies, infiltrative and inflammatory cardiomyopathic syndromes, stroke prevention in atrial fibrillation, high-risk device extractions, electrosurgery, autonomic modulation, and personalized medicine. These programs connect the deep resources and multiple disciplines at all Mayo Clinic locations into teams providing comprehensive clinical evaluation and treatment.

As an enterprise, our specialists annually evaluate more than 15,000 outpatients, review more than 400,000 ECGs and holter exams, and perform more than 6,000 invasive electrophysiology procedures. Our quality improvement program actively monitors procedural outcomes and complications. Newer service lines include the Integrated Cardiac Sarcoid Clinic, Heart-Brain Clinic, needle-electrode and proton beam ablation for ventricular tachycardia, His-pacing for cardiac resynchronization, and artificial intelligence/ECG analysis.

Dr. William J. Mayo said, “The best interest of the patient is the only interest to be considered, and in order that the sick may have the benefit of advancing knowledge, union of forces is necessary.” Our arrhythmology teams at Mayo Clinic are those “union of forces,” as they serve our patients with this commitment each and every day. Members of our team follow on subsequent pages, highlighting their interests and expertise. We would be honored and privileged to participate in the care of any patients who seek this unique medical sojourn we call The Mayo Clinic.

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Artificial Intelligence-Enabled ECG Screening

Advances in computing power so that large amounts of data can be quickly analyzed have made feasible the application of artificial intelligence (AI) to huge, complex data sets. Deep learning architectures – one of a family of AI methods based on learning data set representations – have been applied to diverse fields such as speech recognition, social network filtering, bioinformatics, drug design, and medical image interpretation. One of these deep learning architectures, the convolutional neural network, is especially helpful in the evaluation of high-resolution medical imaging. Subtle variations in a data set can be identified, extracted, and compiled. Convolutional neural networks are being increasingly used to detect hidden features that predict occult disease.

The collaborative Mayo Clinic Cardiovascular AI team is actively exploring the ways that AI can be used to improve patient care. The group has published the results of their study utilizing AI ECG analysis to predict the presence of left ventricular dysfunction in asymptomatic patients. Using Mayo Clinic stored digital data, researchers first screened paired EKG and transthoracic echocardiograms to identify the population to be studied for analysis, and then trained and validated the system. Because ECGs involve repeating complexes, both spatial and temporal dimensions were analyzed. The sensitivity, specificity, and accuracy of this algorithm were 85%, 86%, and 86%, respectively. Additionally, when the network suggested a low ejection fraction (EF) based on ECG findings but the echocardiographic EF was normal, patients had an estimated five-fold increased risk of developing a low EF in the future, suggesting that the network may reveal silent abnormalities hidden in the ECG.

Within Mayo Clinic Department of Cardiovascular Medicine, interdisciplinary teams are applying AI to some of the most challenging clinical problems. Exciting examples include:

• Early risk prediction of conditions such as embolic stroke
• Predicting the risk of developing cardiomyopathies
• Occult disease detection, such as identifying atrial fibrillation’s earliest, subclinical stages, through heart physiology signals transmitted by mobile ECG

Convolutional Neural Network (CNN). Schematic diagram of the architecture of the CNN utilized by the Mayo Clinic AI cardiovascular team to predict the presence of symptomatic left ventricular dysfunction on the basis of subtle ECG findings.
Augmented and Virtual Reality Revolutionize Cardiac Imaging

Augmented reality (AR) and virtual reality (VR) describe disruptive innovative technologies that have the potential to vastly change the landscape of cardiology practice and approach to patient care. VR is a completely simulated, interactive, and computer-generated experience. Any type of sensory feedback can be incorporated; although most environments utilize visual and auditory feedback, medical systems frequently also incorporate tactile feedback. AR involves real-world objects and environments overlaid seamlessly with computer-generated perceptions. AR starts with the real world and alters the environment, while VR creates a totally simulated world.

AR has been particularly useful in the generation of 3D imagery. Real-world structures can be subtracted, virtual structures added, procedures simulated in a step-by-step manner, and outcomes demonstrated. This technology is particularly helpful when planning new, uncommon, or complex procedures and demonstrating the treatment plan to patients and their families. Surgeons and congenital cardiologists at Mayo Clinic are already using this technology routinely. In the future, surgeons will be able to incorporate the AR image spatially into the real-time operative field to guide procedures.

Simulated environments can demonstrate features that cannot be observed in the real world, such as radiation scatter during an imaging procedure. AR and VR that incorporates tactile (haptic) feedback, such as realistic touch, force feedback, and precise motion tracing is exceptionally useful in teaching complex procedures to learners anywhere. Studies suggest that learner retention is superior in the VR environment than in traditional lecture based teaching. Additionally, VR is ideal for training staff how to handle rare emergency situations in a risk-free, simulated environment.

Researchers across the entire Mayo Clinic enterprise continue to explore the application of these pioneering technologies to advance the science and improve patient care. Currently, the AR/VR team is focused on four investigative lines:

• Augmented Thinking – how to create relevant interfaces between humans and the digital world
• Enhancing Interventions – integrating data from various imaging modalities – the echocardiogram, the MRI, the intracardiac map – into one comprehensive image
• Enhancing Surgical Procedures – creating virtual operative suites with virtual patients in which learners – anywhere – can refine their skills
• Enhancing Anatomical Perspective – segmenting imaging data so that 3D images can be easily and economically created – and accessed – anywhere in the world

Innovative and inventive, and no longer improbable. In the near future, these powerful technologies will be an integral part of everyday health care.
Delivering Innovation to Our Patients

The Center for Innovation was developed to continue the history of the Mayo Clinic of investing in innovative best practices by supporting and rapidly developing unique ideas in the health care environment. In the late 1800s, Drs. William J. and Charles H. Mayo founded their medical practice around the concept of an integrated team, a disruptive idea for the times. They knew then what Mayo Clinic continues to acknowledge today: Innovation does not happen by chance.

Members of the Division of Heart Rhythm Services are actively engaged in many aspects of innovative health care delivery. Experimental laboratories provide the means to test and refine prototypical devices in animal models in both the acute and chronic setting. Utilizing this experience the safety and efficacy of devices can be established and refined prior to engaging in human studies.

A cornerstone of device innovation is improving the safety and efficacy of atrial fibrillation ablation. Currently, the two major means of ablation are thermally based (radiofrequency or cryoablation), and have the potential for complications such as pulmonary vein stenosis, atrio-esophageal fistulas, and creation of thrombus and microemboli. Catheters that leverage the use of DC energy to perform electroporation as a non-thermal means of ablation are in development. Electroporation provides the means to selectively ablate muscle sleeves in the pulmonary veins without causing pulmonary vein or esophageal trauma. Another catheter under development selectively targets the epicardial cardiac ganglia via the oblique sinus, utilizing a percutaneous epicardial-based approach to further improve the efficacy of atrial fibrillation ablation as well as minimize unnecessary cardiac or esophageal tissue ablation.

Also under development is a device that is applied to the epicardium in order to provide pacing as well as defibrillation, and thus the option for percutaneously placed cardiac resynchronization therapy without the need for surgical intervention. This approach is ideal in patients who have contraindications to indwelling cardiac leads or anatomical constraints.

Currently there are no good therapies for treating heart failure with preserved ejection fraction, more commonly known as HFpEF. This group is substantial and makes up about 50% of patients with heart failure. Several tools and a process for effective percutaneous pericardial resection have been developed, resulting in improved cardiac hemodynamics. This innovative strategy is in its early stages of feasibility testing in patients.

There is major interest in treatment for neurocardiogenic syncope. For individuals in whom there is sudden, severe vasodilation, syncope can occur precipitously and without warning. Understanding the role of renal artery denervation in the treatment of hypertension, researchers innovatively reciprocated the thought process and has devised a means to stimulate these nerves and thus the sympathetic system to create a counter-surge in catecholamines during symptoms. Also under investigation is a non-thermal means of ablation with electroporation to denervate the renal vasculature and offer a non-pill form of treatment to a tremendously large population of patients with hypertension.
A Tradition of International Service and Collaboration

Perhaps the most significant global health challenge we will face in upcoming decades will be the exponential increase in the worldwide burden of chronic disease, especially cardiovascular disease. Many individuals are living longer due to better (but still imperfect) control and treatment of infectious diseases, but are concurrently adopting negative aspects of “western” lifestyles, including high sodium, high fat, and high calorie diets, sedentary lifestyles, and smoking. These lifestyle changes have resulted in a rapid increase in the worldwide incidence and prevalence of hypertension, diabetes mellitus, obesity – and cardiovascular disease.

One consequence of globally increased longevity and the increased prevalence of coronary artery disease has been and will continue to be many more individuals developing arrhythmias including bradycardias, atrial fibrillation, and ventricular arrhythmias, but without access to sophisticated monitoring, cardiologists and electrophysiologists, and facilities and equipment.

Our founders, Drs. William J. and Charles H. Mayo, believed strongly in the value of global collaboration to “advance the science” and treat the patient. They both travelled widely throughout their careers, teaching and learning from colleagues around the world. That spirit remains alive and well across the Mayo Clinic enterprise. Pediatric and adult electrophysiologists from Mayo Clinic have provided services, including diagnostic studies, ablations, device monitoring, and complex device management to underserved national and international sites for many years. The division collaborates with international colleagues to share best-practices and processes, and to facilitate prompt access to Mayo Clinic heart rhythm services. Regional appointment coordinators and referral facilitators help international patients arrange appointments. Patients who travel to any of the Mayo Clinic sites will find an International Center, with staff that can assist patients with registration, embassy approvals, appointment coordination, travel arrangements, and financial matters; the centers also provide language services, international pharmacists, and nursing staff.

The management of arrhythmias requires a comprehensive approach in which the electrophysiologists work with colleagues who have expertise in primary and secondary prevention so as to address the causes and not just the consequences. New and refined technology will provide additional opportunities to support our international patients and their local providers. Those tools include secure mobile phone platforms for remote monitoring, individual real-time consultations with patients and providers, and secure health data transmission. Diagnostic and therapeutic procedures via remote robotics are on the horizon, allowing providers at Mayo Clinic to direct procedures remotely. Genomic analysis will be increasingly important to our international patients. Augmented and virtual reality environments will provide opportunities to review individualized procedures with providers world-wide.

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Broadening the Perspective for Cardiac Regeneration

Stem cells, with their unique potential to trans-differentiate into different tissues, have transformed the way we think about how the body repairs itself. The cardiac regeneration effort at Mayo Clinic began 20 years ago. This work has since culminated in clinical efforts spanning beyond adult cardiology to include cardiac surgery, pediatric cardiology, and vascular medicine, with active efforts in heart failure, Ebstein’s Anomaly, Hypoplastic Left Heart Syndrome, and refractory angina.

The discovery that stem cells derived from patients with heart failure had variable regenerative potency was a critical landmark. By identifying uniquely activated cues in regenerative subpopulations, cells could be coaxed to adopt a highly regenerative state. Termed cardiopoietic stem cells, this specialized cellular population demonstrated a heightened aptitude towards cardiac repair. To standardize the assessment of therapeutic potency in the heart, a cardiopoietic index has been developed to allow objective assessment of the regenerative potential of patient-derived stem cells. Moreover, clinical-grade production of these cells at scale provided the capability to translate this platform from the bench to the bedside.

The cardiopoietic stem cell experience, and other efforts within the Center for Regenerative Medicine by investigators in the Department of Cardiovascular Medicine and across the enterprise, have created a team with unique expertise in product development, manufacturing, quality assurance, and FDA-regulated clinical trial execution. To this end, the new challenge in this field is to take an inherently variable autologous (from the patient) cell population and engineer new platforms that provide reliability in dosing, potency, and efficacy. The emergence of automated bioreactor systems in manufacturing, synthetic messenger RNA platforms, and increasing expertise in creating allogeneic (from the donor) master cell banks provide the opportunity to engineer allogeneic cell platforms devoid of the variability seen with their autologous counterparts. Beyond cell therapy, with increasing understanding of the mechanistic basis for regeneration in the heart, systems devoid of living cells are increasingly being considered.

Regenerative technologies devoid of cells would have the capability of activating repair-signaling pathways to mimic stem cell action in the heart. Since it is increasingly apparent that stem cell benefit is likely due to a paracrine mechanism of action rather than direct integration, acellular approaches are of increasing interest. Implementation of a cell-free regenerative paradigm provides additional benefits including the ability to have clear dosing algorithms, assured homogeneity in function, and elimination of logistical hurdles that often complicate cell-based therapeutic models. The evolution of biologics-based technologies, in tandem with the 21st Century Cures Act, has encouraged a more rapid advancement of regenerative platforms. Mayo Clinic has built new readiness in this space with dedicated infrastructure to serve as a supply chain for regenerative technologies and to address unmet patient need. The Mayo Clinic regenerative portfolio builds on the already robust cellular effort to now implement trials using extracellular vesicles and gene therapy, a next chapter in the evolving regenerative toolkit.
Enhancing Patient Safety

One of the major concerns during mapping and ablation of arrhythmias is the risk of thrombus formation on catheter tips, which can then embolize to the brain and other organs. Anticoagulation reduces the risk of this complication, but cerebral embolization documented by brain imaging continues to occur. More aggressive anticoagulation regimens increase the risk of bleeding complications. The process of thrombus formation on intra-cardiac catheters begins with fibrinogen deposition on the electrodes. Researchers at Mayo Clinic in Florida have demonstrated that by continuously depositing negative charge on catheter electrodes, it is possible to repel fibrinogen molecules and minimize the initiation and progression of thrombus formation. Multiple animal studies have demonstrated the efficacy of this approach, including reduction of cerebral thromboembolism. This technique has many potential biological and medical applications outside of the electrophysiology laboratory.

During intra-cardiac ablation, there is an ongoing compromise between the amount of force applied to tissue (to improve ablation efficacy) and the risk of perforation due to excessive force. Advanced signal processing techniques are being investigated for use during arrhythmia mapping and ablation to improve efficacy and safety of ablation procedures. By examining fine detail in the intra-cardiac electrograms, it is possible to predict catheter contact force without needing a separate mechanical force sensor. Also, subtle details buried in noise or pacemaker artifact can now be visualized, adding valuable information on tissue electrical properties at arrhythmogenic sites before and after ablation.
The Mayo Clinic Windland Smith Rice Comprehensive Sudden Cardiac Death in the Young Program

Over 20 years ago, the Mayo Clinic in Rochester, Minnesota started a combined bench-to-bedside program devoted to patients and their families at risk of premature sudden cardiac death secondary to a variety of genetic heart rhythm diseases (GHDs), also known as the cardiac channelopathies. Under the direction of Michael J. Ackerman, MD, PhD, the Mayo Clinic Windland Smith Rice Genetic Heart Rhythm Clinic has evaluated over 3300 unique patients including the diagnosis, risk stratification, and tailoring of a personalized treatment program for more than 1300 patients with genetically confirmed long QT syndrome (LQTS). This represents the largest single center cohort of patients with LQTS in the United States and one of the largest single center cohorts in the world.

Besides LQTS, the Genetic Heart Rhythm Clinic sees a very large number of patients with catecholaminergic polymorphic ventricular tachycardia (CPVT), Brugada syndrome (BrS), hypertrophic cardiomyopathy (HCM), arrhythmogenic cardiomyopathy (ACM), families of unexplained sudden cardiac death victims, patients with arrhythmogenic bileaflet mitral valve prolapse syndrome, and young out-of-hospital cardiac arrest survivors. In addition, the clinic has removed the diagnosis of LQTS and other GHDs in more than 500 patients who have been diagnosed erroneously elsewhere. In some cases, not only the diagnosis of LQTS has been removed but their ICD has been removed as well.

Overall, the clinic has overseen the return-to-play for the largest number of competitive athletes with GHDs in the world and has the world’s largest single center experience with videoscopic left cardiac sympathetic denervation surgery as a treatment option for patients with LQTS, CPVT, and other GHDs.

The basic, translational, and clinical research activities of this program take place in the Mayo Clinic Windland Smith Rice Sudden Death Genomics Laboratory. Dr. Ackerman and his research team have published more than 550 peer-reviewed manuscripts that have included the discovery and functional characterization of novel disease-causing genes for LQTS, CPVT, BrS, HCM, and ACM, the elucidation of genotype-phenotype relationships, and the outcomes of known and novel treatment strategies for the various GHDs.

Some current areas of sudden death study include:

• New gene discovery in the pathogenesis of GHDs
• Functional characterization of novel GHD-associated genes and variants
• Variant interpretation and promotion/demotion of variants into and out of “genetic purgatory”
• Genotype-phenotype correlations of GHDs
• Catecholamine provocation testing in the evaluation of congenital LQTS
• Sleep and neural circulatory control in LQTS
• Clinical evaluation of novel risk factors, treatment of GHDs
• Development of novel (mobile) ECG-devices to detect GHDs
In addition, there are many ongoing retrospective and prospective studies and clinical trials. The close relationship of the research laboratory and the clinical practice provide the basis for performing impactful translational and genotype-phenotype correlation studies. Stemming from this hand-glove relationship between research and practice, this program has built a biorepository that comprises over 2000 patient DNA samples. In addition, over 500 patient-specific, GHD-specific induced pluripotent stem cell (iPSC) lines have been established to enable a variety of “disease-in-the-dish” and “treatment-in-the-dish” cardiac cell studies.

Besides these efforts for the living, Dr. Ackerman pioneered the Molecular Autopsy twenty years ago and has performed postmortem genetic testing on nearly 1000 sudden death victims to try to establish “cause and manner” of death to provide closure and clarity for the families left behind. This effort has been translated into national and international guidelines for the proper procurement of DNA-friendly tissue to enable such forensic genetic investigations. In 2019, with a partnership between Dr. Ackerman’s program and Mayo Clinic’s Department of Laboratory Medicine and Pathology, Mayo Clinic now offers a truly comprehensive autopsy (gross, microscopic, toxicologic, and now genetic) for victims of unexplained and unexpected sudden cardiac death.

Dr. Ackerman’s research team also collaborates with other scientists at Mayo Clinic and all around the world. Led by Dr. Ackerman, the Windland Smith Rice Sudden Death Genomics Laboratory has advanced the training of nearly 100 pre/postdoctoral students and research fellows. The Windland Smith Rice Genetic Heart Rhythm Clinic and the Windland Smith Rice Sudden Death Genomics Laboratory at Mayo Clinic in Rochester, Minnesota have become one of the most comprehensive “bedside-to-bench-and-back again” programs in the world for families affected with LQTS and the other sudden death-predisposing genetic heart conditions.
Looking Towards the Future

The arrhythmia research program at Mayo Clinic encompasses a wide range of interests and disciplines from basic science, to clinical trials and translational approaches. An important mission of the program is to involve residents and fellows – our future medical researchers – in designing and directing specific projects. Some of our researchers and their focus:

Hon-Chi Lee, MD, PhD directs the arrhythmia research program in addition to his own ion channel research laboratory. He is known for his work on the regulation of ion channels in the cardiovascular system using biochemical, molecular, and electrophysiological techniques. Dr. Lee is the leading expert on understanding the dysregulation of large conductance calcium-activated potassium channels, which are targets of endothelium-derived hyperpolarizing factors in diseases such as diabetes. His recent research interests focused on novel mechanisms of cardiac arrhythmia and cardiovascular diseases with emphasis on immune-autoimmune activation by oxidative stress. Specific ongoing projects include:

- Molecular mechanisms of cardiovascular aging with lessons from progeria. Using animal models of progeria, he is studying the role of progerin on development of oxidative stress and the cause of cardiovascular dysfunction and fibrosis through immune activation.
- Vascular function and atrial fibrillation. Dr. Lee has made the novel finding that atrial coronary microvessels from patients of paroxysmal and persistent atrial fibrillation have impaired shear stress-mediated vasodilation. He is examining the role of oxidative stress and immune activation in the development of arterial stiffening and microvascular dysfunction in patients with atrial fibrillation.
- Dr. Lee is exploring new genes in cardiovascular diseases using zebrafish technology. Using animal models of genetic knockout, he is examining the role of Sorbs2 in the development of cardiomyopathy, sudden cardiac death, atrial fibrillation, and vasculopathy.
- The role of Nrf2, a transcriptional factor and a master regulator of cellular redox, in the development of diabetic channelopathy, cardiovascular fibrosis, and development of cardiac arrhythmias.

Samuel J. Asirvatham, MD is the vice-chair of cardiac innovation. His research is focused on innovative equipment design and novel techniques that improve treatment for arrhythmias. Current endeavors include:

- Development of percutaneous epicardial systems to close the left atrial appendage
- Design and application of ablation hoods to entrap “bubbles” and microemboli during cardiac ablation
- Development of novel epicardial multisite pacing electrodes not involving the coronary sinus for cardiac resynchronization
- Effective cardiac defibrillation through cardiac cooling
- Device for effective treatment of HFpEF through pericardial modification
- The use of pulse electrical field for treatment of atrial fibrillation, coronary artery diseases, and renal denervation

THOUGHT LEADERS

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Samuel J. Asirvatham, MD
Douglas L. Packer, MD, former president of the Heart Rhythm Society and recipient of the American College of Cardiology Distinguished Scientist Award (Translational), was the principal investigator for the multicenter randomized trial comparing the effect of percutaneous catheter ablation versus antiarrhythmic drug therapy in patients with atrial fibrillation (CABANA). He is now studying whether percutaneous catheter ablation also has a favorable effect on survival, stroke, quality of life, and health care costs. Additional efforts include:

- Development of a needle electrode catheter, which allows for the extension of heated saline via needle tip into the tissue to create larger lesions. Research suggests that this technique may be superior to contact force ablation and cryoablation for some arrhythmias

- Use of external photon beam and carbon beam radiation to target arrhythmogenic cardiac tissue and produce sustained, as well as controllable, antiarrhythmic effects – no intracardiac catheters required

Suraj Kapa, MD focuses on translational innovation as well as elucidating basic mechanisms underlying electrophysiological diseases. He also engages in clinical research to evaluate quality metrics and optimal approaches to currently available methods of electrophysiological treatments. Dr. Kapa’s current projects include:

- Use of biocompatible material-embedded carbon nanotubes to help re-circuit electrophysiological substrates in the beating heart

- Development of novel mapping techniques for atrial fibrillation, specifically studying methods of identifying and localizing rotors, which are thought to be responsible for the perpetuation of atrial fibrillation

- Understanding the incidence and best approaches to treatment of arrhythmias in rare cardiac diseases, including left ventricular noncompaction, complex adult congenital heart disease, and sarcoidosis

- Development of tools and techniques for modification of electrophysiological substrate using novel energy sources, including electroporation, sonoporation, and active biological agents for more targeted arrhythmia treatment
ECG-Enabled Textiles Offer New Cardiac Monitoring Networks

A new approach to rhythm monitoring is via sensors embedded directly in the fibers of clothing. ECG-enabled textiles are a new form of wearable medical technology giving rise to the era of “smart heart clothing.”

Smart heart clothing holds the potential to offer 24/7 heart rhythm monitoring remotely, and to detect rhythm abnormalities early. The rapid intervention this makes possible can significantly improve earlier detection and treatment of conditions such as atrial fibrillation. Current technology requires patients to be on site for equipment hook-up. Smart heart clothing is more compatible with remote health data collection and transmission, and will increase the ability to reach patients from anywhere in the world. It will also increase the ability to identify those individuals likely to benefit from traveling to a Mayo Clinic site for treatment.

Smart heart clothing is intended to replace various long term monitoring devices, which can be cumbersome to use. Current monitoring technology is limited by the following disadvantages, which ECG-enabled clothing seeks to overcome. Patients:

- Must travel to a health care center to get the device
- Undergo a procedure that requires affixing sticky electrical leads to a patient’s chest
- If male, sometimes ECG connections requires that chest hair is shaved
- Can risk having leads fall off, interrupting monitoring and diminishing data quality
- Face restricted movement, such as showering or other daily activities

As smart heart clothing development proceeds and prototypes are adopted, embedded textile sensors may be used to detect and record other health data such as temperature, respiration rate, and activity levels. The current focus is on resolving regulatory and manufacturing issues, ensuring data privacy is protected, and refining the software. But smart heart clothing will be leading the change in the way patients receive care, and it will usher in an era of more accessible, comfortable physiologic monitoring.
Inpatient Services

The Heart Rhythm Division at Mayo Clinic in Rochester, Minnesota is supported by three distinct hospital services: an inpatient service, an inpatient consultative service, and an outpatient observation interventional service. The inpatient service manages patients with a variety of arrhythmic issues including atrial fibrillation and flutter, other supraventricular tachycardias, ventricular tachycardia, and a spectrum of bradyarrhythmias. Patients with other monitoring requirements such as syncope of uncertain cause, severe electrolyte abnormalities, and potentially arrhythmogenic repolarization abnormalities are also cared for by this service.

Many patients for whom anti-arrhythmic therapy is recommended are admitted to the inpatient service to begin drug therapy while being continuously monitored. The requirement for hospitalization is determined by the severity of the arrhythmia and the choice of antiarrhythmic agent. Mayo Clinic arrhythmia specialists have developed protocols that ensure the rapid initiation of drug therapy to minimize the duration of patient hospitalization while maintaining patient safety. Protocol-driven drug administration has reduced the length of stay for these patients by a full 24 hours. The suitability for drug administration is identified per protocol in the outpatient department. The inpatient service is staffed by trained electrophysiologists and multiple advanced practice providers with an interest in arrhythmias. This service operates 24/7 with an average census of 16 patients and an average length of stay of 3.5 days.

The interventional service manages patients admitted from the outpatient department after electrophysiology or device procedures. The service is staffed by highly trained advanced practice providers with supervision from the interventional electrophysiology procedural staff. The patient length of stay is typically less than 48 hours. The team supervises expedited dismissals within hours of procedures eliminating overnight stays in patients without significant comorbidity or complex procedures.

The inpatient consultative service provides assistance to all hospital inpatient services with questions or concerns related to abnormalities of cardiac rhythm. This service is staffed 24/7 with an average census of 15 patients. It also provides miscellaneous services such as emergent implantation of temporary pacemakers and after-hours device interrogations. The inpatient services collaborate with clinical trial investigators and quality specialists, and provide a robust experience for trainees.
Tackling the Most Challenging Arrhythmias

The presence of dynamic, integrated clinical and research teams at Mayo Clinic allows us to offer a wide array of complex procedures and management programs for patients seeking comprehensive arrhythmia care in a high volume setting. Safe, efficient, and expert multidisciplinary care is one of our chief strengths.

Mayo Clinic has more than 50 years of institutional experience in arrhythmia ablation, including surgical, catheter-based, and hybrid approaches. Detailed endocardial and epicardial 3D and 4D mapping have been performed on-site for more than 30 years. All contemporary mapping systems, as well as several various energy sources are utilized. The group is actively investigating new techniques including needle-electrode radiofrequency and proton-beam radiotherapy energy sources for the treatment of structural ventricular tachycardia.

Device implantation for bradycardia, heart failure, and sudden death management, and active remote monitoring of patients and their devices now numbers more than 10,000. There are active protocols for His-pacing as an alternative to traditional cardiac resynchronization (CRT), subcutaneous pacing, CRT in patients with ejection fraction of 35-50%, and phrenic nerve stimulation for sleep apnea or diaphragmatic paralysis. The lead extraction program integrates knowledge and procedural acumen from interventional cardiology, interventional radiology, pulmonology, cardiovascular surgery, infectious diseases, and plastic and general surgery to achieve optimal outcomes for our patients.

Atypical atrial flutter activation map showing early breakout in the posterior left atrium.

Epicardial substrate voltage (left) and activation (right) maps showing extensive low voltage (red) areas that correlate with late activating myocardium that is part of the slow zone of the ventricular tachycardia circuit.

Endocardial left ventricular reentrant ventricular tachycardia showing isthmus “channel” of viable tissue between scars (gray) as target for catheter ablation.

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CLINICAL EXCELLENCE
Additionally, niche programs include treatment of pulmonary vein stenosis, left atrial non-compliance syndrome (diastology), complex adult congenital heart disease, left atrial appendage stroke management, cardiac sarcoidosis, and genetic channelopathy syndromes. Potential therapies include pulmonary vein stenting, atrial septostomy, autonomic modulation (catheter and surgical based), autoimmune therapy, pharmacologic/cell therapies for amyloidosis, as well as surgical treatment for hypertrophic cardiomyopathy, Ebstein’s Anomaly, and other congenital anomalies associated with arrhythmias.

The division is integrating augmented and virtual reality equipment into our laboratories for the 21st century. These platforms will allow us to network with colleagues globally, while enhancing the experience of both the proceduralist and learner in our lab environments. An active artificial intelligence program is also being incorporated into both non-invasive and invasive aspects of our practice to facilitate discovery and value. We remain ever excited as the frontiers of tradition and science push forward.
Preventing Stroke in Patients with Nonvalvular Atrial Fibrillation

Embolization of thrombus from the left atrial appendage (LAA) is responsible for more than 90% of strokes in patients with nonvalvular atrial fibrillation. Anticoagulation is the most commonly used strategy for stroke prevention, and multiple clinical trials have demonstrated the efficacy of this approach. Direct oral anticoagulants have expanded options for anticoagulation in these patients.

Nevertheless, for many patients systemic anticoagulation is either relatively or absolutely contraindicated by virtue of a history of life-threatening bleeding, drug-drug interactions, severe fall risk, or anticoagulant failure. Current risk models do not incorporate anatomic and functional aspects of the LAA such as emptying velocity, which are likely important.

All of these factors have made attractive local site therapy with a device to anatomically exclude the LAA from the circulation. Mayo Clinic cardiologists were instrumental in the development of the only approved transcatheter-deployable device, the WATCHMAN™ device (Boston Scientific). Since its FDA approval, approximately 30,000 patients have been treated with a WATCHMAN™ device and it has been studied in two randomized clinical trials and multiple registries.

While the procedure can be performed using general anesthesia guided by transesophageal echocardiography, increasingly patients are being treated under moderate sedation using ICE guidance. The procedure may be performed by interventional cardiology, interventional electrophysiology or, preferably, by both given the fact that both disciplines bring important approaches to the field.

In randomized clinical trials which were used for device approval and for which we now have greater than five-year follow up, the following messages have been confirmed:

• Procedural device implantation success is seen in approximately 95% of patients undergoing the procedure.
• Pericardial effusion occurs in 1.5-2.0% of patients, but rarely requires intervention.
• Procedural related stroke is seen in ≤ 1% of patients.
• During follow up, by one year, 90-95% of patients do not require any further anticoagulation for stroke prevention.
• The major overall hard events can be seen in the five year data from the two randomized trials PROTECT AF and PREVAIL. As noted, they include that overall, the rate of all strokes is similar despite the fact that patients with the WATCHMAN™ device are not typically on an anticoagulant. This similarity relates to the fact that not all strokes in patients with nonvalvular atrial fibrillation are related to the LAA or that the occlusion is suboptimal.
• There is a dramatic reduction (approximately 80%) in hemorrhagic stroke in patients treated with the WATCHMAN™ device as compared to warfarin.
• There is an improvement in survival in patients treated with the WATCHMAN™ device as compared with anticoagulation with warfarin and bleeding is significantly less.
<table>
<thead>
<tr>
<th>Event</th>
<th>HR</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficacy</td>
<td>0.082</td>
<td>0.3</td>
</tr>
<tr>
<td>All stroke or systemic embolization</td>
<td>0.96</td>
<td>0.9</td>
</tr>
<tr>
<td>Ischemic stroke or systemic embolization</td>
<td>1.7</td>
<td>0.08</td>
</tr>
<tr>
<td>Hemorrhagic stroke</td>
<td>0.2</td>
<td>0.0022</td>
</tr>
<tr>
<td>Ischemic stroke or systemic embolization &gt;7 days</td>
<td>1.4</td>
<td>0.3</td>
</tr>
<tr>
<td>CV/unexplained death</td>
<td>0.59</td>
<td>0.03</td>
</tr>
<tr>
<td>All-cause death</td>
<td>0.73</td>
<td>0.04</td>
</tr>
<tr>
<td>Major bleed, all</td>
<td>0.91</td>
<td>0.6</td>
</tr>
<tr>
<td>Major bleeding, non procedure-related</td>
<td>0.48</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

Meta-Analysis: PROTECT AF and PREVAIL (5 Years)
The Best of Both Worlds: Hybrid Catheter Ablation

Since its advent over two decades ago, percutaneous catheter ablation has become the mainstay of arrhythmia management. Previously, patients required medical therapy or open cardiac surgery. Early surgical experience was harbored through accessory pathway ablation and subsequently moved towards atrial and ventricular arrhythmias. Multiple energy sources have been utilized including physical interruption-division, radiofrequency and more recently, cryoablation. All have the same goal, namely to generate scar thereby fashioning an electrically inert region to eliminate the abnormal rhythm. While catheter ablation has circumvented the need for surgical ablation in many cases, certain situations provide a unique opportunity whereby a combination of catheter and surgical ablation may improve patient outcomes, (so called hybrid ablation). Though novel ablation catheters (e.g. needle irrigated catheter) and techniques (e.g. non-invasive ablation) are attracting attention, these remain research modalities. Furthermore, not all patients are candidates for these approaches. As such, there has been an increasing trend towards hybrid ablation combining the skillsets of cardiac electrophysiologists and cardiovascular surgeons to optimize procedural outcomes. This has been shown to be useful in numerous situations, including where the arrhythmic focus is inaccessible (for example, in cases of an epicardial focus in a patient with prior cardiac surgery), juxtaposed to a critical structure (e.g. close to coronary artery), or where traditional ablation techniques are unable to deliver sufficient energy to eliminate the target source.

Hybrid ablation has greatly enhanced our ability to deliver state of the art cardiovascular care. A myriad of hybrid procedures for both atrial and ventricular arrhythmias are currently offered and performed at Mayo Clinic.

Atrial Arrhythmias

Atrial fibrillation (AF) is the most common cardiac arrhythmia seen in clinical practice. Ablation has been shown to be superior to medical therapy alone. Unfortunately, outcomes remain suboptimal in part due to the difficulty in achieving full thickness, transmural lesions and due to concern for collateral damage with excessive ablation. Therefore, combined endocardial-epicardial ablation represents an attractive approach to circumvent this issue either as a first line or alternative approach depending on patient characteristics. Epicardial ablation is performed using minimally invasive techniques (unless performed during concomitant cardiac surgery) in which the cardiac surgeon works closely with the cardiac electrophysiologist to devise an optimal lesion set. Typically, the left atrial appendage is also removed during the surgical procedure which helps both reduce recurrent AF and subsequent thromboembolic stroke risk. The patient then undergoes completion endocardial ablation typically performed at a later date.
Radiofrequency ablation during open cardiac surgery. This can be performed in minimally invasive fashion also if only a selected region of interest is targeted.

**Ventricular Arrhythmias**
Individuals with structural heart disease and ventricular tachycardia (VT) often have suboptimal outcomes despite repeated ablation procedures. Oftentimes, this is related to extensive scar and incomplete substrate elimination which may lie deep within the myocardium or on the epicardium. The standard epicardial approach is not always possible in those patients who have had previous cardiac surgery, and intramyocardial or epicardial substrate may be inaccessible with conventional techniques. In any patient with previous cardiac surgery, epicardial ablation is best done with surgical access. Therefore, hybrid ablation in concert with a surgeon represents an attractive option. In this, the surgeon can create a surgical window over the region of interest. In addition to obtaining access, surgical colleagues participate in mapping and ablation with the electrophysiologist overseeing electrophysiological measurements.

Patients with left ventricular assist devices (LVAD) represent a unique population. Over 30% of LVAD recipients develop VT, even if they have no history of VT beforehand. Though this is initially well tolerated given the hemodynamic support from the LVAD, recurrent or ongoing ventricular arrhythmias are associated with reduced quality of life, recurrent defibrillator therapies, and even increased mortality. Though endocardial ablation can be performed following surgery, the LVAD cannula and epicardial adhesions from surgery prohibit epicardial ablation. As such, pre-operative electrophysiology study and ablation with completion at the time of surgery represents a novel approach to management of this high risk population. We have a dedicated team of advanced heart failure physicians, cardiac surgeons, and cardiac electrophysiologists who work closely together to optimize management protocols for such individuals to optimize outcomes.
Caring for Our Smallest Patients

In addition to the excellent care provided for adults, Mayo Clinic provides world class care to pediatric patients from before birth to beyond adolescence. Mayo Clinic has two physicians trained specifically in pediatric rhythm disturbances and pacemakers, both certified in pediatric electrophysiology by the International Board of Heart Rhythm Examiners (IBHRE), the primary certification provider for pediatric electrophysiology. Additionally, Dr. Cannon is board certified in Adult Congenital Heart Disease. Drs. Wackel and Cannon provide care for a wide variety of arrhythmias and are able to provide treatment options including medications, potentially curative ablation procedures as well as pacemakers and ICDs.

New and innovative techniques allow for invasive arrhythmia treatment in even the smallest patients. Currently over 100 pediatric electrophysiology procedures are performed annually and have a 100% procedural success rate for ablations for supraventricular tachycardia. The newest technology allows over half of these procedures to be performed with no radiation exposure. Several types of ablation energy are available so that the procedures can be performed as safely as possible.

Drs. Wackel and Cannon are very active in clinical research having published over 90 peer reviewed pediatric electrophysiology journal articles and over 10 textbook chapters, and have spoken at over 100 national and international conferences. Dr. Cannon is a co-author of two international pediatric electrophysiology guideline documents; one on the ablation of arrhythmias in pediatric patients, and the other on the management of Wolff-Parkinson-White syndrome. Their research involves application of all of the complex technologies available in medicine to young patients with rhythm disturbances.

Bryan C. Cannon, MD
President, Pediatric and Congenital Electrophysiology Society
Mayo Clinic in Rochester, Minnesota

Ablation procedure using a 3D mapping system.
Philip L. Wackel, MD
Mayo Clinic in Rochester, Minnesota

ICD placement in a 4 month old child.
Expanding the Role of Device Therapy

Cardiac device therapy has been utilized in clinical practice for 60 years; traditional pacing indications include sinus node dysfunction and atrioventricular block. Recent decades have seen the development of life-saving ICD therapy, hemodynamic pacing, and implantable remote monitors. Indications and options continue to expand due to clinical trial results and advancing technology. Device specialists across the enterprise are offering new therapies for patients.

Leadless Pacemaker
Transvenous leads are vulnerable to blood stream infection, may result in obstruction of the venous system, may be a nidus for paradoxical thromboembolism, and may lead to tricuspid valve regurgitation. Leadless devices can be used for single chamber right ventricular pacing. These devices can be considered in individuals who have chronic atrial fibrillation with bradycardia or planned atrioventricular node ablation, infrequent but symptomatic sinus pauses, recurrent transvenous system infection, or individuals without transvenous access.

Physiological His Bundle Pacing
The conventional right ventricular pacing results in ventricular dyssynchrony as the conduction is from the paced right ventricle to the left ventricle in a sequential manner, and may worsen left ventricular function and heart failure. In His bundle pacing, the pacing lead is on or near the His bundle. As His bundle pacing directly captures the conduction system, it results in a narrow QRS complex, eliminating the adverse effects of right ventricular apical pacing. In some patients who have chronic left bundle branch block, His bundle pacing results in a narrow QRS complex.

Subcutaneous Implantable Cardioverter Defibrillator (SICD)
Different from transvenous ICD, SICD lead is placed subcutaneously in the left chest along the sternal border, and the generator is located in the left axillary area. As the entire device is extravascular, it can be considered in patients with recurrent bacteremia, venous obstruction, congenital heart disease, tricuspid valve abnormalities, or to avoid lead complications in young patients with a life-long need for device therapy.

Extravascular Implantable Cardioverter Defibrillator (EICD)
The defibrillation lead of EICD is placed in under the sternum, which is different from SICD where the lead is placed above the sternum. The generator is placed in the left axillary area. As the shock lead is just anterior to the heart (intrathoracic), it requires a lower energy to defibrillate than SICD systems. EICD can deliver pacing therapies, although the pacing output is usually higher than transvenous systems. As in SICD, EICD systems do not require entry into the patient’s venous system or cardiac chambers.
Lead Extraction
Mayo Clinic research has demonstrated that not all failed leads need to be extracted; many can simply be capped and a new lead inserted. In instances of infection or vascular compromise, lead extraction is required. Factors that increase the risk and the difficulty of extraction include age of patient, the duration of the lead implant, and the presence of multiple leads. Our providers have a full menu of tools with which to extract device leads and they work as teams with cardiac and vascular surgeons; complex and high-risk extractions are done in hybrid rooms with cardiopulmonary bypass immediately available in the event of damage to myocardium, valvular structures, or the vasculature. Venoplasty and stenting can be performed on stenoses that have formed around leads in venous system. Plastic surgeons join when extensive debridement is involved. Despite the complexity of these procedures, complication rates associated with lead extraction at Mayo Clinic are well below national averages.

Cardiac Resynchronization Therapy (CRT)
CRT is a nonpharmacological therapy for patients with severe heart failure. It has now been clearly proven that CRT can improve chronic left ventricular systolic dysfunction, heart failure symptoms, quality of life, and survival. Nevertheless, approximately a quarter of individuals do not experience a favorable response to CRT therapy. Mayo Clinic provides a team approach to managing CRT non-responders, incorporating device and hemodynamic specialists, heart failure specialists, and comprehensive hemodynamic evaluation. An exciting new opportunity involves leadless left ventricular pacing, allowing for CRT therapy in patients with difficult or suboptimal transvenous left ventricular lead placement options without a thoracotomy.
Setting the Bar: Continuous Quality Improvement

Providers across the entire Mayo Clinic enterprise strive to provide the highest quality care to each and every patient. A component of that effort is actively identifying and monitoring procedural complication rates. A physician-led team manually reviews records at the time of discharge and then again at 30 days. Quarterly data is summarized and then analyzed by operator, by case, and by complication, and complication rates that exceed threshold are investigated. Despite providing care to some of the most complex patients, we are pleased that we are able to consistently maintain complication rates well below the national average.

### Ablation Procedural Complication Rates

- **Tamponade with Centesis**
  - Ntl. Avg. 1.0%
  - 2016: 1.5, 2017: 0.5, 2018: 1.3

- **Stroke**
  - Ntl. Avg. 0.5%
  - 2016: 0, 2017: 0.2, 2018: 0.3

- **TIA**
  - Ntl. Avg. 0.5%
  - 2016: 0, 2017: 0, 2018: 0.3

- **Pulmonary Vein Stenosis 0-90 days**
  - Ntl. Avg. 0.5%
  - 2016: 1.4, 2017: 0.6, 2018: 0.3

---

Robert F. Rea, MD  
Quality Director  
Mayo Clinic in Rochester, Minnesota
Device Procedural Complication Rates

<table>
<thead>
<tr>
<th>Procedure</th>
<th>% Occurrence</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pneumothorax Requiring Chest Tube Placement</td>
<td>3</td>
<td>0</td>
<td>0.28</td>
<td>1</td>
</tr>
<tr>
<td>Hematoma Requiring Exploration and/or Transfusion</td>
<td>2-</td>
<td>0.38</td>
<td>0.07</td>
<td>0.44</td>
</tr>
<tr>
<td>Lead Dislodgement</td>
<td>3—</td>
<td>1.4</td>
<td>1.5</td>
<td>1.35</td>
</tr>
<tr>
<td>Infection</td>
<td>3—</td>
<td>0.38</td>
<td>0.8</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Ntl. Avg.

Athletes Finding Their Rhythm

Mayo Clinic is the first hospital in Arizona to pioneer comprehensive and specialized care for the investigation and treatment of cardiac arrhythmias in adult athletes. Partnering with colleagues in the Divisions of Sports Medicine and Sports Cardiology, tailored arrhythmia services are provided for professional, amateur, student, and master athletes alike. Athletes with conditions such as Wolff-Parkinson-White, supraventricular and ventricular arrhythmias, and syncope as well as athletes with implanted cardiac devices are treated and advised with the goal of safe performance and expedited return to sporting activities. The Sports Electrophysiology Service focuses on the athlete’s health and safety in the context of their sport modality.
Historical Timeline

- 1914: Fredrick A. Willius, MD obtains Cambridge ECG machine and performs first Mayo Clinic ECG
- 1914: First transcutaneous epicardial pacing
- 1914: Ralph Smith, MD develops computerized ECG to store tracings and provide preliminary analysis
- 1914: Benjamin D. McCallister, MD inserts first temporary transvenous pacing electrode
- 1914: Dwight C. McGoon, MD performs first ever intraoperative procainamine injection to abolish WPW
- 1914: John Meredith, MD organizes first pacemaker clinic
- 1914: Ralph Smith, MD transmits ECG by phone to Australia
- 1914: Gordon K. Danielson, MD surgically divides accessory pathway guided by intraoperative mapping
- 1914: James D. Maloney, MD performs first diagnostic EP study, a His bundle evaluation
- 1914: John Meredith, MD named director of pacemaker/EP group
- 1914: Remote telephone monitoring of pacemakers
- 1914: James D. Maloney, MD named director pacemaker/EP group
- 1914: David R. Holmes, Jr, MD does first pacemaker implant in cardiac laboratory
- 1914: David R. Holmes, Jr, MD named first director formalized device/EP laboratory
- 1914: David L. Hayes, MD implants first DDD pacemaker
- 1914: Stephen C. Hammill, MD performs first AVN ablation
- 1914: Mayo Clinic EP training program established - Douglas L. Wood, MD the first EP fellow
- 1914: Michael J. Osborn, MD named director device/EP laboratory
- 1914: Douglas L. Wood, MD and David R. Holmes, Jr, MD perform first VT ablation
- 1914: Hartzel V. Schaff, MD implants first ICD
- 1914: Stephen C. Hammill, MD named director of device/EP laboratory
- 1914: Douglas L. Packer, MD performs first RFA for PSVT
- 1914: David L. Hayes, MD implants first transvenous ICD
- 1914: Thomas R. Flipse, MD performs first PSVT ablation at Mayo Clinic in Florida
- 1914: Douglas L. Packer, MD performs first PVI
- 1914: David L. Hayes, MD named president of the North American Society of Pacing & Electrophysiology
- 1914: David L. Hayes, MD named director of the device/EP laboratory
- 1914: Luis R. Scott, MD develops and is named director of the dedicated Heart Rhythm Service at Mayo Clinic in Arizona
- 1914: Luis R. Scott, MD implants first biventricular pacemaker in Arizona
- 1914: David R. Holmes, Jr, MD implants first LAA occlusion device.
- 1914: Stephen C. Hammill, MD named president of the Heart Rhythm Society
- 1914: Andre Terzic, MD, PhD named president of the American Society for Clinical Pharmacology and Therapeutics
- 1914: Fred Kusumoto, MD named director of Heart Rhythm Services at Mayo Clinic in Florida
- 1914: Fred Kusumoto, MD performs first PVI at Mayo Clinic in Florida
- 1914: Luis R. Scott, MD performs first epicardial VT ablation in Arizona
- 1914: Michael D. McGoon, MD named president of the Pulmonary Hypertension Association
- 1914: Douglas L. Packer, MD named director of Heart Rhythm Services, Mayo Clinic in Rochester, Minnesota
- 1914: Mayo Clinic in Arizona starts EP training program. Erik Wissner, MD is first EP fellow
- 1914: Douglas L. Packer, MD named president of the Heart Rhythm Society
- 1914: Win-Kuang Shen, MD named chair of Division of Cardiovascular Diseases, Mayo Clinic in Arizona
- 1914: Komandoor Srivathsan, MD named director of Heart Rhythm Services training program, Mayo Clinic in Arizona
- 1914: Thomas R. Flipse, MD implants first subcutaneous ICD at Mayo Clinic in Florida
- 1914: Paul A. Friedman, MD implanted first leadless pacemaker at Mayo Clinic in Rochester, Minnesota
- 1914: Fred Kusumoto, MD named president of the Florida Chapter of the American College of Cardiology
- 1914: Thomas M. Munger, MD named chair of Division of Heart Rhythm Services, Mayo Clinic in Rochester, Minnesota
- 1914: K. M. Venkatachalam, MD and Peter Pollak, MD develop the integrated LAA management program at Mayo Clinic in Florida
- 1914: K. M. Venkatachalam, MD performs first leadless pacemaker implant at Mayo Clinic in Florida
- 1914: Paul A. Friedman, MD named chair of Department of Cardiovascular Disease, Mayo Clinic in Rochester, Minnesota
- 1914: Thomas R. Flipse, MD named director of the Cardiac Device Clinic at Mayo Clinic in Florida
- 1914: Luis R. Scott, MD named chair of Department of Cardiovascular Diseases, Mayo Clinic in Arizona
- 1914: Yong-Mei Cha, MD implants first wireless LV pacing device
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Christopher J. McLeod, MB, ChB, PhD launches EP training program at Mayo Clinic in Florida
Preparing our Future Colleagues

The Mayo Clinic Cardiac Electrophysiology Training Program began in 1980, and since then more than 100 cardiac electrophysiologists have been trained. The program in Rochester, Minnesota was developed and led by Stephen C. Hammill MD, and subsequently by Samuel J. Asirvatham, MD. The training program at Mayo Clinic in Arizona began in 2007 under the auspices of Luis R. Scott, MD and was subsequently led by Komandoor Srivathsan, MD. The Mayo Clinic in Florida program launched in 2020. Initially a one-year program, it has expanded into a two-year program and is accredited by the Accreditation Council for Graduate Medical Education. It is anticipated that five fellows will complete training annually across the enterprise.

The two-year cardiac electrophysiology program provides comprehensive training in the basics of electrophysiology, complex mapping and ablation procedures, device implantation, lead extraction, and overall device management and troubleshooting. With the changing epidemiology of arrhythmias throughout the world, atrial fibrillation has emerged as the most common arrhythmia, with treatment by non-pharmacological and invasive approaches, some of which were pioneered at Mayo Clinic. Trainees develop experience managing paroxysmal and persistent atrial fibrillation, ventricular arrhythmias, complex congenital arrhythmias, and device complications. Both epicardial and endocardial ablations are routinely performed allowing trainees to receive comprehensive exposure to these procedures and associated technologies.

The trainees also rotate with the pediatric cardiac electrophysiology group in order to gain a more nuanced understanding of supraventricular arrhythmias, accessory pathways, and device management in this population.

A real strength of the program is underscoring the very basics of practicing safe and effective electrophysiology, with a focus on anatomy, electrogram assessment, biophysics, and complementary imaging techniques. Trainees participate in weekly didactic sessions including device conferences, case-based discussions, and grand rounds. There are multiple opportunities for clinical, basic, and translational research. Most of the trainees publish multiple manuscripts during their fellowship training program.

The main objective of the program is to train cardiac electrophysiologists able to perform complex electrophysiological procedures safely and effectively, becoming seasoned professionals who will be leaders, innovators, and educators in the field of cardiac electrophysiology.
Abhishek J. Deshmukh, MBBS
Co-Director, Electrophysiology Training Program
Mayo Clinic in Rochester, Minnesota

Blue Pins: Current practice sites of graduates of the Mayo Clinic in Rochester, Minnesota training program.

Red Pins: Current practice sites of graduates of the Mayo Clinic in Arizona training program.

By The Numbers

- **Over 100,000** Device Interrogations Annually
- **10** CME Courses
- **5,000** Inpatient Evaluations Annually
- **Over 400,000** ECGs and Extended Monitoring Devices Annually
- **Approximately 3,000** Cardiac Implantable Devices Annually
- **1** Board Review Course
- **100** EP Fellows Trained
- **Over 50** Youtube Videos
- **Over 15,000** Outpatient Evaluations Annually
- **Approximately 3,000** Electrophysiology Procedures Annually
- **Over 3,000** Cardiac Implantable Devices Annually

- **Over 15,000** Device Interrogations Annually
Mayo Clinic in Rochester Minnesota

Thomas M. Munger, MD
Chair, Division of Heart Rhythm Services

Paul A. Friedman, MD
Chair, Department of Cardiovascular Medicine

Samuel J. Asirvatham, MD
Director, Electrophysiology Laboratory
Director, Education

Hon–Chi Lee, MD, PhD
Director, Research

Margaret A. Lloyd, MD, MBA
Director, Clinical Practice

Michael J. Osborn, MD
Director, Inpatient Services

Yong-Mei Cha, MD
Director, Device Laboratory
YOUR TEAM

Michael J. Ackerman, MD, PhD
Director, Genetic Heart Rhythm Clinic
Director, Windland Smith Rice Sudden Death Genomics Laboratory

Robert F. Rea, MD
Director, Safety and Quality

Andre Terzic, MD, PhD
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