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CRYOABLATION OF CARDIAC ARRHYTHMIAS

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Cryoablation of Cardiac Arrhythmias

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To my father and mentor, Jurgis Bredikis; my mother, Danute; my wife, Egle; and children, Jurgis and Audre

—A.B.

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Preface

The purpose of this text is to provide a comprehensive resource on cryoablation, including tissue effects, cryotechnology, and clinical applications.

Cryoablation has unique properties that are very different from other energy sources used for ablation of cardiac or other tissues. Because freezing has minimal effects on elastic collagen structures and has less-detrimental effects on local microcirculation, tissue "architecture" remains preserved to some extent and tissues also heal better. This decreases the risk for stricture formation, stenosis, and ulceration of ablated areas. These features of cryoablation are especially useful when lesions have to be placed in close proximity to important cardiac structures such as the His bundle, pulmonary veins, coronary arteries, esophagus, and phrenic nerve.

Despite all these attractive features, cryoablation is underutilized because the more complex catheter design decreases maneuverability and the cryocatheters that are currently commercially available operate at –80°C, requiring longer application times.

Recently developed balloon-based cryotechnology, as well as the availability of "colder" technologies utilizing critical nitrogen, super-critical nitrogen (–180°C to –196°C), and other agents, has the potential to overcome these limitations and increase utilization of cryoablation in electrophysiology laboratories. Further development of these technologies will be extremely useful for ablation of ventricular tachycardia and for septal ablation in hypertrophic cardiomyopathy.

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Contents

Section I

Fundamental Aspects of Cryoablation

Chapter 1

History of Cardiac Cryosurgery and Cryoablation

Daniel L. Lustgarten, MD, PhD

KEY POINTS

- The concept of using cryoenergy to treat medical illness has been present since the dawn of recorded history.
- Specific application of cryoenergy as a therapeutic modality depended on practical application of the Joule-Thomson effect.
- Invasive application of cryotherapy in the heart lagged behind other disciplines because of the relatively recent appreciation of the role of ablating abnormal cardiac substrate to treat arrhythmias.
- The history of cardiac cryotherapy reflects progressively less invasive and more specialized delivery systems.

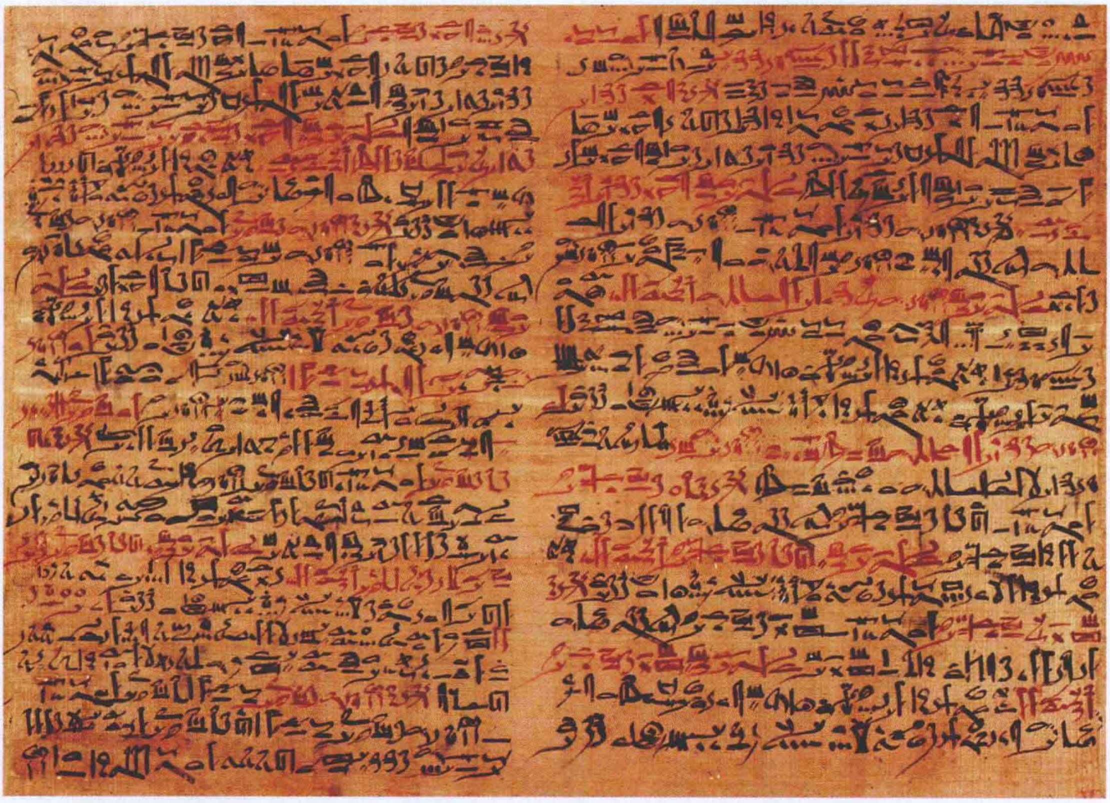
Robert Slama and colleagues[1] in Paris reported on surgical ablation of the atrioventricular (AV) node in patients with drug-refractory atrial arrhythmias in 1967. Subsequently, Will Sealy[2] at Duke University described successful surgical interruption of a right lateral accessory pathway in a 32-year-old fisherman with Wolff–Parkinson–White syndrome. These publications represent the birth of interventional electrophysiology, providing proof of concept that arrhythmias could be cured or alleviated by destroying cardiac tissue requisite for their clinical manifestation. Soon surgeons, in collaboration with their electrophysiologist colleagues, extended these findings to the management of supraventricular arrhythmias and ventricular tachyarrhythmias. However, incisional approaches to treating arrhythmias required open-heart surgery, typically requiring cardiopulmonary bypass, associated with significant morbidity and mortality.[2,3] The use of surgical electrocautery, formalin injection, and tissue ligation were all associated with disruption of the normal tricuspid valvular apparatus, ventriculoseptal defects, and injury to the aortic sinuses.[4] Therefore, from the inception of arrhythmia surgery, the search for less invasive approaches and ablative modalities was ongoing.

Although cryoablative approaches were studied during these early years of interventional electrophysiology, radiofrequency became the dominant ablative energy source because of the relative simplicity of radiofrequency-based catheter systems and the discrete targets of arrhythmias being treated. However, the extensive lesion sets associated with atrial fibrillation ablation and substrate-based ablation for scar-mediated ventricular tachycardia (VT) make cryoablation an attractive alternative to heat-based modalities, in that cryoablation may be less likely to cause collateral damage. The feasibility of using cryoablation for this purpose entered the practical realm with the realization that the Joule–Thompson effect could be applied to intravascular catheters to deliver ablative levels of cold energy. This chapter reviews the history of this technologic leap with a view toward providing perspective on the present and future roles of cryoablation in arrhythmia management, which is the topic of the ensuing chapters.

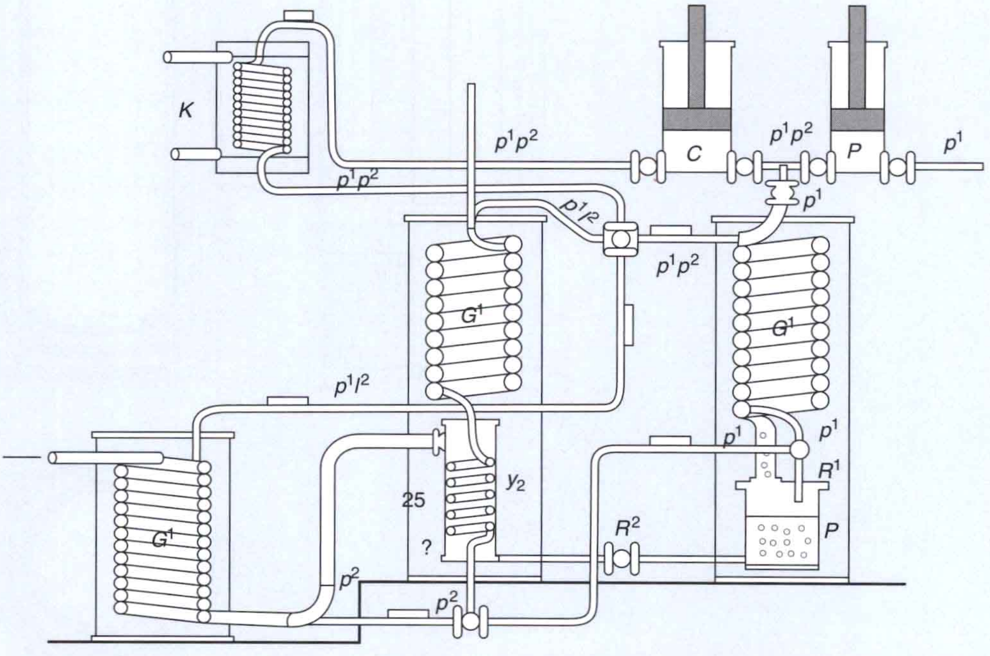
JOULE–THOMSON EFFECT

Intravenous catheter-delivered cryoenergy—that is, cold enough to destroy cardiac tissue—was made possible by the practical application of the Joule–Thomson effect, and it represents a fascinating chapter in the history of medicine. The alleviating effects of cryotherapy were appreciated at the dawn of medical history, with reference to the use of cold to treat battlefield injuries present in the oldest known medical document, the Edwin Smith papyrus (Figure 1–1). Writings attributed to Imhotep and his pupils (2600 BC) were discovered on papyrus that was purchased in Luxor in 1862 by Egyptologist Edwin Smith.[5] These writings specify the ingredients of cold compresses (figs, honey, and grease) to be applied to battle injuries. However, the notion that cold energy could be used to destroy diseased tissue required the ability to harness and deliver cryoenergy at extremes of cold far exceeding those of compresses, a notion that would take nearly four millennia to manifest.

During the Industrial Revolution, two major innovations occurred that ultimately set the stage for the modern conception of cryotherapy and ultimately cryocatheter-mediated mapping and ablation. One was the discovery and production of powerful refrigerants. In 1853, James Prescott Joule and Henry Thomson reported that the temperature of a real gas would vary depending on the initial temperature and pressure with expansion at constant enthalpy. Allowing compressed gas to rapidly expand below the gas's inversion temperature resulted in dramatic cooling caused by loss of kinetic energy. Carl Paul Gottfried von Linde (1842–1934) capitalized on the Joule–Thomson effect to make the first commercially viable refrigerant.[6] Von Linde developed vapor-compression refrigeration machines, the first iteration of which used dimethyl ether as the refrigerant. His apparatus for the liquefaction of air combined the cooling effect achieved by allowing a compressed gas to expand with a countercurrent heat exchange technique that used the cold air produced by expansion to chill ambient air entering the apparatus (Figure 1–2). This gradually cooled the apparatus and air within it to the point of liquefaction.



■ **Figure 1–1** Part of the Edwin Smith papyrus containing teachings attributed to Imhotep.



■ **Figure 1–2** Von Linde's original patent design.

A system was needed that would allow the storage and transfer of frozen liquefied gases, for refrigerants to be applied medically. This second major innovation came in the form of the vacuum flask invented in 1892 by the Scottish physicist and chemist James Dewar (1842–1923).[7] The thermos consists of a vessel within a vessel separated by a vacuum, the latter preventing heat transfer by conduction or convection, with radiant heat loss being minimized with the use of silver-lined glass. The Dewar flask enabled storage, transfer, and ready access to fluids at temperatures less than −180°C, setting the stage for the medical application of cryogens. An example of an early patented version of a Dewar flask submitted by Reinhold Burger to the U.S. Patent Office in 1907 is shown in Figure 1–3. With these innovations in place, it was now possible for medical scientists to test the effects of extreme cold on biological tissues.

In the first half of the 20th century, liquid refrigerants were used to destroy tumors and skin lesions by surface application. Refrigerants were applied at temperatures less than −70°C to achieve cell death. In 1961, a handheld cryoprobe that would permit surgical application of cryoenergy was invented through collaboration between the renowned New York City neurosurgeon Irving Cooper, and Arnold Lee, an engineer from the Linde division of Union Carbide Corporation.[8] The handheld cryoprobe design is, in essence, a marriage between the concept of

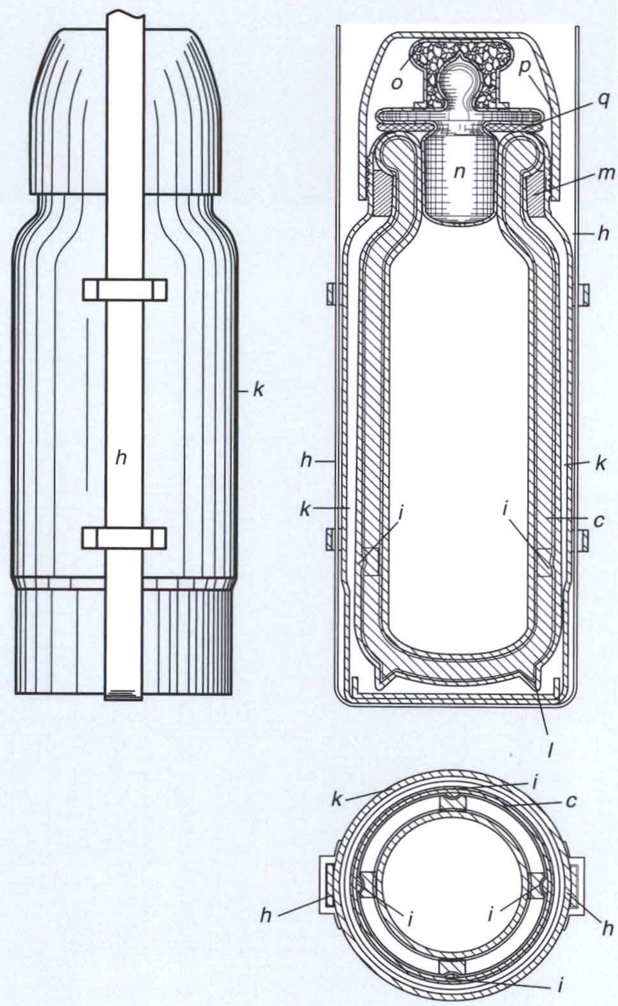


Figure 1–3 An early Dewar flask patent.