Historical Development of Cardiac Pacing*

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I would like to discuss the development and historical aspects of cardiac pacemaking from a personal point of view, presented as it appeared to me over the years. This approach is biased, selective, and incomplete, but I think as informative as I can make it.

It has long been known, indeed from the early days of Galvani, that electrical currents have effects on the heart. The knowledge that a cardiac contraction may result from an electrical stimulus led to no clinically useful result until relatively recently Other instances are common perhaps even at the present time in medicine in which basic information is available for advances in therapy but is not being used.

There was not much change in this field until about 1900, when a great deal of research was conducted on the effects of electrical currents on the heart. It was demonstrated in physiological and pharmacological laboratories then that electrical stimuli produced action currents that were conducted along nerve or muscle cells, and produced contractions in skeletal, smooth, and cardiac muscle. Among the important contributors were Adrian, Evans, and John Erlanger In 1900, Prevost and Batelli demonstrated that electrical currents, both direct-current and alternating-current discharges, would terminate ventricular fibrillation. The shocks were applied directly to the heart, but it took a very long time again before this information was used effectively In 1933, Hooker, Kouwenhoven, and Langworthy made extensive and valuable laboratory studies on the effects of alternating current in terminating ventricular fibrillation, again the current was applied directly to the exposed heart. This work was extended in 1936 by Ferris, King, Spence, and Williams, who demonstrated that capacitor discharges also terminated ventricular fibrillation. They used sheep, relatively large animals, with hearts similar to man's in size, but again information lay dormant without human, clinical application. In 1946, some Russian workers, Gurvich and Yuniev, recorded very briefly in the English literature that capacitor discharges would terminate ventricular fibrillation. About 1940, Wiggers and Wégria conducted extensive experimental studies outlining the various features of electric shock that were useful in terminating ventricular fibrillation. Wiggers demonstrated that an initial alternating-current shock might produce ventricular fibrillation in a normally beating heart and a second shock of the same nature but perhaps a little stronger might terminate the fibrillation. Wiggers applied the term "countershock" to this procedure, which I like to use and keep alive despite current usage of other terms because of its historical significance. I think we should give him credit for providing us with the sound experimental basis for the technique of defibrillation which has saved so many lives. The first clinically successful termination of ventricular fibrillation in man was done in 1947 by Beck, Pritchard, and Feil, who resuscitated a patient from ventricular fibrillation by performing emergency thoracotomy, direct cardiac "massage," and application of alternating current to the exposed heart. In this very brief review of direct ventricular defibrillation, I have passed over some instances in 1902 and 1910 of defibrillation that were unsuccessful. In 1947, Claude Beck and his group in Cleveland had established that opening the chest and applying a-c countershock would terminate ventricular fibrillation, this procedure formed the basis for the treatment of cardiac arrest that was widely taught and vigorously practiced in those days. In the presence of cardiac arrest, under any circumstances one was supposed to cut the chest open, "massage," i.e. squeeze the heart rhythmically to provide an effective output, and if necessary to defibrillate the heart by direct application of alternating-current countershocks.

In 1932, Dr Albert S. Hyman in New York City addressed himself to the parallel problem of ventricular standstill. He attempted to develop an effective means of stimulating the heart in ventricular standstill so as to terminate cardiac arrest. He applied a stimulus from an electric pacemaker to the atrium by passing a long needle or electrode through the chest wall into the atrial musculature. He demonstrated effective atrial stimulation in the rabbit by this technique, but it was never applied successfully in man as far as I know A major difficulty lay in the maintenance of good contact of the needle electrode in the cardiac

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muscle without displacement or injury Another problem was in the application of the stimulus to the atrium, in clinical cardiac arrest atrioventricular block is often present so that atrial beats are not conducted and do not arouse ventricular contractions.

In their extensive studies in 1940, Wiggers and Wégria examined the effects of electric stimuli of varying intensity and duration at varying intervals after a preceding beat, and clearly delineated the various phases of cardiac excitability They demonstrated and applied the term "vulnerable phase" to the interval in the relative refractory period when a strong (well above threshold for a single response) or long stimulus produces multiple or repetitive beats and even fibrillation. The stimuli used in these studies were 10 milliseconds long, whereas present-day pacemakers provide stimuli usually less than 2 milliseconds long. This explains why they were able to demonstrate repetitive responses and the vulnerable period so readily

I became interested in electric stimulation of the heart shortly after World War II, after I had observed much of the pioneering cardiac surgery done by Dr Dwight Harken for the removal of foreign bodies in and about the heart. The heart appeared, indeed, to be a very sensitive organ that responded readily with ventricular contractions to stimuli, arousal from ventricular standstill by appropriate stimulation should, therefore, not be difficult. The other point with which I was impressed I should have learned in first-year anatomy—the esophagus lies behind the heart in very close contact with it. Thoracotomy and direct electrical stimulation of the heart seemed to be an inappropriate and excessively traumatic approach to the problem of effective cardiac stimulation that was not much better than the universally accepted program of thoracotomy, cardiac massage, and direct countershock defibrillation. It seemed to me that a stimulus might arouse a ventricular contraction in a patient with cardiac arrest if it were applied in the esophagus close to the heart by way of a long wire electrode passed down the mouth.

I thought about this matter for some time but did not do much about it, I am afraid, for a long while. My background in electricity was inadequate, so I did not know how to build a pacemaker that would provide an appropriate stimulus. In 1950, William C. Callaghan, a Canadian cardiac surgeon, spoke at a Boston Surgical Society meeting and described an approach of passing a wire electrode "catheter" down the jugular vein in a dog, and stimulating the area of the sino-atrial node to provide an effective rhythm controlled by an external pacemaker This method has not been used clinically but it is very interesting and it contains elements of many of our present-day techniques, especially the idea of applying an electric stimulus by way of a pervenous endocardial "catheter" wire electrode. He made a great effort to apply it to the sino-atrial node, not an appropriate site for ordinary clinical purposes in patients with A-V block, but one that is being reconsidered for special purposes now I found that he used a standard physiologic pacemaker made by the Grass Instrument Company in Quincy, Mass., and within the next year I managed to borrow one from Dr Otto Krayer, head of the Pharmacology department of the Harvard Medical School. With a long wire electrode in the esophagus and a second electrode over the precordium in a dog, I was quickly able to demonstrate that electrical stimuli would indeed arouse atrial or ventricular electrical responses and effective muscular contractions with which cardiac arrest could be terminated and the circulation maintained. An extensive laboratory study was undertaken to develop the details of this new technique of external electric stimulation of the heart, to improve and simplify the procedure and the apparatus, to define its clinical applicability and limitations, and to expose any associated hazards. It was soon found that rather large currents were necessary for effective stimulation (30 to 150 volts or 50 to 200 milliamperes) unless the negative electrode actually touched the heart, and that two surface electrodes on each side of the precordium were as effective as an esophageal-precordial pair Short stimuli, 2-3 milliseconds in duration, were selected when they were found to be almost as effective as longer ones in stimulating single responses and never produced repetitive responses, tachycardia, or fibrillation except in hearts seriously damaged by ischemia, anoxia, or overdoses of digitalis or quinidine.

In 1952, we applied the method of external electric stimulation for the first time in man, and it quickly became established as an effective emergency means of arousing the heart from ventricular standstill. Although most frequently used in patients with Stokes-Adams disease, it was also effective in standstill of any origin, even in the absence of A-V block, so long as cardiac contractility was not overly depressed by prolonged anoxia or drugs. Although external stimulation was occasionally used in desperate circumstances for hours or days to maintain an artificial rhythm, it proved too painful for ordinary long-term use. For the purposes of arousing, accelerating, and maintaining intrinsic ventricular rhythms in patients with high-degree A-V block, Dr Arthur J Linenthal and I developed the method of intravenous administration of dilute solutions of sympathomimetic amines, particularly epinephrine and isoproterenol. Combined use of the two methods often enabled us to keep patients alive through intervals of severely unstable rhythm and frequent Stokes-Adams attacks.

We also found at that time that provision of a rapid regular rhythm by external electric stimulation or by acceleration of an intrinsic pacemaker pharmacologically would often stop recurrent ventricular tachycardia and fibrillation. This demonstration lies behind the concept of overdriving the heart to suppress multiple competing rhythmic foci, which is an important aspect of present-day control of cardiac rhythm with electric pacemakers.

The method of external electric cardiac stimulation is based on the idea of applying a large electric current to the surface of the chest so that a small portion of it may reach the heart and stimulate a response, just as a small electric stimulus applied directly to the exposed heart was known to do. The success of this technique suggested modification of the usual countershock defibrillation after thoracotomy by application of a large countershock externally across the surface of the chest. In 1954, contemporaneously with William Kouwenhoven at Johns Hopkins and Arthur C. Guyton at the University of Mississippi, we developed a technique for *external* electric countershock defibrillation with large 60-cycle alternating-current shocks in dogs and domestic pigs. The next year we applied it successfully for the first time to resuscitate a patient from ventricular fibrillation. We also demonstrated in the laboratory that external a-c countershock would terminate every type of rapid arrhythmia. atrial tachycardia, atrial fibrillation, ventricular tachycardia, and ventricular fibrillation. In 1955, we terminated several desperate attacks of ventricular tachycardia and in 1957 one of atrial tachycardia in man with external a-c countershock. In 1961, Bernard Lown at the Peter Bent Brigham Hospital greatly modified this approach by applying external direct-current shocks (obtained by capacitor discharge through an inductance) that were synchronized to fall immediately after the R wave so as to avoid the vulnerable phase of the cardiac cycle. He used this method, which he termed "cardioversion," for the elective termination of lesser arrhythmias with the thought that synchronization would prevent the production of ventricular fibrillation. Although some disagreement with this view persists (from myself and other workers as well), the technique of synchronized d-c shock is most generally used today The initial enthusiasm for cardioversion of minor arrhythmias has subsided considerably because of the frequent early recurrence of the arrhythmia with little clinical benefit.

The development of these two methods of external electric stimulation and of external electric countershock led to great changes in the management of cardiac arrest. With effective emergency means of arousal of the heart from standstill and of defibrillation without the need for thoracotomy, programs of action became simpler, less traumatic, and more successful. The unpredictability of attacks and the limited time available for resuscitation pointed to the need for prompt recognition of the onset of arrest and identification of the arrhythmia. From our early experiences with patients with Stokes-Adams disease came the development of cardiac monitors in 1954 that provide an audible signal of each beat, continuous visual display of the electrocardiogram, an alarm signal of appropriate changes in rate, and prompt, even automatic availability of an external electric pacemaker In 1960, William Kouwenhoven developed the technique of "external cardiac massage," or external cardiac compression, by which circulation of blood may be restored immediately in the emergency of cardiac arrest and, if necessary, the time interval for more definitive management of arrhythmia may be extended.

In 1963, Hughes Day combined all these techniques and applied them to patients with acute myocardial infarction, the largest group with serious arrhythmias. He placed patients with this condition under continuous monitoring in a coronary care unit where monitors, pacemakers, and defibrillators were concentrated together with personnel expert in their use and trained in a program for management of cardiac arrest. His demonstration in the pioneer unit at Bethany, Kansas, of a major reduction in mortality from acute myocardial infarction led to the widespread acceptance of the concept of the coronary care unit.

It seems unfortunate to me, however, that the idea of continuous cardiac monitoring has not been applied widely to surgical operating rooms where unexpected cardiac arrest still occurs with significant frequency and mortality In 1963, Drs. Morris Nicholson and Joseph Crehan, anesthesiologists at the New England Deaconness Hospital in Boston, monitored a number of very sick patients throughout anesthesia. In this group they demonstrated a striking improvement in successful resuscitation from cardiac arrest. Despite this convincing experience, continuous cardiac monitoring with automatic alarm has not become a standard part of the management of all patients undergoing anesthesia, as I believe it should.

The final subject of discussion is the development of internal cardiac pacemakers for the long-term provision of a reliable rhythm at any rate desired. The need for a method of prolonged cardiac stimulation was obvious early in our experience with patients with Stokes-Adams disease, when we were able to resuscitate patients from attacks of standstill or fibrillation but were unable to prevent recurrent episodes. Direct cardiac pacing with small, imperceptible electric stimuli by means of electrodes implanted in the myocardium had long been known and used experimentally, but for years long-term pacing in this way was frustrated by a progressive rise in threshold for stimulation. In 1958, Thevenet, Hodges, and Lillehei in Minneapolis attempted to stimulate the heart directly in patients with Stokes-Adams disease with a stainless-steel electrode placed in the myocardium at thoracotomy that was connected to an externally carried pulse generator Stimulation failed uniformly within 7 weeks, however, because of increasing threshold for cardiac response. We finally recognized the problem as a foreign-body tissue reaction to minute, sterile contaminants on the electrode surface and solved it by using inert metals for the active electrode (platinum, gold, or stainless steel) and by boiling it in Ivory soap flakes. Dr Samuel A. Hunter in St. Paul developed the Hunter-Roth electrode and with it was the first in 1959 to achieve long-term pacing in a patient with Stokes-Adams disease. In 1960, Drs. William Chardack, Adrian Kantrowitz, and Howard Frank and I began series of implantations of pacemaker-electrode systems by way of thoracotomy, and adequate long-term management of A-V block and Stokes-Adams disease was finally accomplished.

Many problems arose and many changes were made in long-term cardiac pacing to meet them. Displacement of electrodes, wire breakage, and component failure in the pulse generator have in large measure been corrected, but early battery depletion remains the major difficulty at present. An important modification, which has become widely accepted, has been in the placement of a pervenous endocardial "catheter" electrode under fluoroscopic control rather than by thoracotomy This approach was first introduced by Drs. Seymour Furman and John Schwedel at the Montefiore Hospital in New York City with the electrode passed through an antecubital vein and connected to an externally carried pulse generator Subsequently, other veins were used and the entire pacemaker system was placed subcutaneously Although the procedure is relatively minor, it is not entirely satisfactory in that electrode placement is sometimes very difficult and even unsuccessful, and electrode displacement, myocardial perforation, high threshold for stimulation, and wire breakage occur with small but significant frequency In this regard, we have recently developed an "arrowhead" electrode that may be inserted rather quickly and securely through a small thoracotomy but under direct vision. This technique is an attempt to gain the advantages of both approaches–secure placement of the electrode in the myocardium but with a relatively small, well-tolerated procedure.

In recent years, many types of pacemakers have been developed to avoid competition of an independent fixed-rate pulse generator with intrinsic beats, which do occur often from ectopic ventricular foci or from return of A-V conduction. It appears that competition offers little risk clinically of repetitive response and ventricular fibrillation, unless an electrode is inserted in an area of acute myocardial ischemia or infarction. Nevertheless, variable-rate ("synchronous," "demand," or "stand-by") pacemakers may at times be advantageous in producing less palpitation and better cardiac output. Atrial-triggered, ventricular-triggered and inhibited, and atrial-ventricular sequential pulse generators of many varieties have been developed, and some are now being widely used.

Presently, both temporary and long-term pacing are also being applied with considerable enthusiasm in a variety of clinical situations and to a wide variety of difficult arrhythmias. Consequently, the area of applicability of cardiac pacing is growing. Advances in technology and engineering also promise major improvements in new generations of pacemakers so that we can anticipate exciting developments in the whole field of electrical control of cardiac rhythm.