THE ARTIFICIAL CARDIAC PACEMAKER

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ITS HISTORY, DEVELOPMENT AND CLINICAL APPLICATION

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Introduction

CHAPTER I

Omni custodia serva cor tuum
quia ex ipso vita procedit

Proverbs IV-23

Electrical stimulation of various organs of the human body was already practiced more than one and a half centuries ago. Applications however did not pass beyond the experimental stage. Only in recent decennia one aspect emerged from this stage to develop into a new therapy – the electrical stimulation of the heart.

This book presents the results of joint research in the field of electrical stimulation of the heart since 1959 at Groningen, Holland. The text is basically identical with that of a 1969 thesis of our cooperator DR. H. J. TH. THALEN. New material on the photo-analysis method and the pacemaker enabling threshold control of the heart has been added in an appendix.

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The authors owe a great deal of gratitude to the many people of their groups, who have all contributed, sometimes quite unaware, by inspiration and by practical help, to the teamwork, to which this book owes its existence.

Although the results of artificial stimulation of the heart appeared

theoretically attractive compared with the usual pharmacological therapy, we observed, as did other authors, many complications in the first clinical applications. Initial complications centred upon the electrodes, and so research was concentrated upon this point, but attempts were also made to perfect the stimulation unit itself (fig. I-1). This led to the development of stimulation units based on completely new principles.
The original purpose of this book was exclusively to describe this research. During a study of the literature however, it became clear that

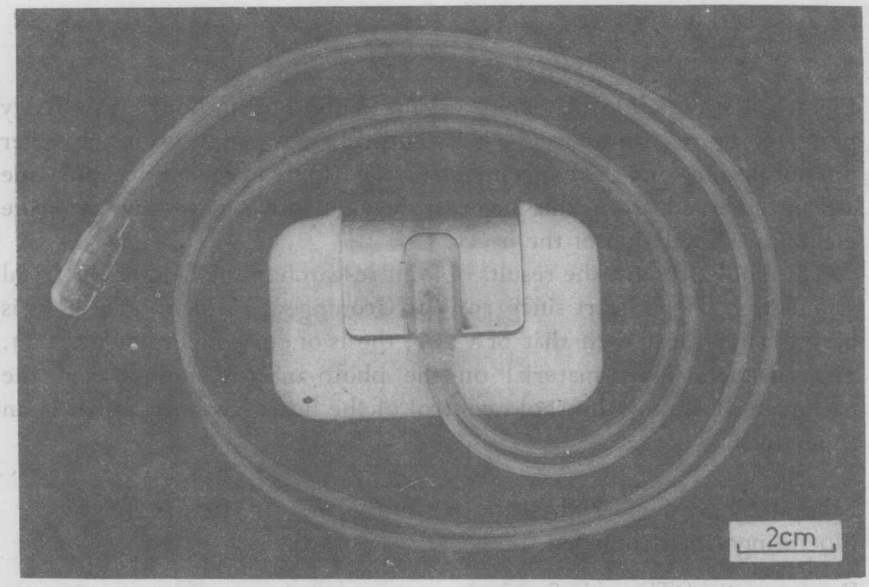

Fig. I-1. Latest version (1967) of the Groningen asynchronous pacemaker in combination with the intramural loop electrode.

there was a serious gap despite the abundance of publications on the subject of cardiac stimulation. This omission was the absence of a systematic survey of literature, and so the lay-out of this book was altered into its present form, such a systematic survey being included in the first chapters. In subsequent chapters our own research is described and the results are used to provide a framework for the above-mentioned survey and a basis for a general discussion of all aspects of the problem.
The subject has been dealt with from a medical-physical viewpoint, and no research was carried out in the field of physiology, e.g. bloodpressure

and cardiac output. Where these factors play a role, use is made of research done by others.

In Chapter II the conduction system of the heart is discussed from this viewpoint, together with the defects to which it is subject, their causes, and the therapeutic possibilities.

Chapter III gives an historical outline of early and recent developments in the field of the stimulation of the heart.

In Chapter IV the now well-known methods of electrical stimulation are dealt with, the principle of each method, animal research and clinical applications being discussed. After the description of each method of stimulation a synopsis is given of the specific advantages and disadvantages.

Then, in Chapter V, the aims and achievements of the Groningen research are discussed. At the same time the various auxiliary apparatus is dealt with. Subsequently the three parts of a stimulation unit are analysed.

Chapter VI is devoted to the various types of electrodes and includes a discussion of the reactions in the surrounding cardiac muscle. Special attention is given to the fundamentals of electrical stimulation.

Chapter VII reviews the transmission of the stimulation impulse from the stimulator to the electrode in the heart.

Finally, Chapter VIII is concerned with the stimulator itself. The basic unit is dealt with initially and the discussion then includes the different kinds of stimulators which have been developed from it.

After the latter three chapters, which together give an insight into the complete stimulation unit, Chapter IX is devoted to the monitoring of the pacemaker patient, with the emphasis being laid on a new method of analysing the implanted stimulator.

The survey of the present state of affairs in artificial stimulation of the heart is concluded in Chapter X, with some observations on future possibilities.

It will be apparent that this thesis is not intended to be a report in which large numbers of patients are analysed in detail. Rather, its purpose is to give an outline of the principles of heart stimulation and the possibilities which exist in this field.

The conduction system of the heart

CHAPTER II

The heart is a complicated network of muscle fibres, which contains four cavities. In order to bring about a good circulation these muscle fibres must contract in a definite sequence. The necessary co-ordination between all portions of the heart muscle is achieved by special heartcells, which form the conduction system of the heart.

When defects of this conduction system are present, therapeutic possibilities are offered by electrical stimulation of the heart.

Before dealing with this electrotherapy, it is necessary to give first an outline of the normally functioning conduction system of the heart, defects of the conduction system and possible causes of these defects.

I. ANATOMY AND PHYSIOLOGY OF THE CONDUCTION SYSTEM

A. Anatomy (fig. II-1)

1. Morphology and localization

Morphologically the conduction system of the heart consists of: a. the sino-auricular node – b. the atrio-ventricular node – c. the atrio-ventricular bundle with – d. the left and the right branches which finally divide into – e. the Purkinje cells.

The S-A node does not in fact conduct stimuli but forms the stimuli. Nevertheless we are discussing this node with the conduction system of the heart since it is both functionally and anatomically closely related with this system.

The A-V node and the A-V bundle with both branches together form the atrio-ventricular conduction system of the heart. This could be considered to include the Purkinje cells.

a. Sino-auricular node. In 1907 Keith and Flack found cells in the sulcus terminalis situated by the recess of the vena cava superior in the right atrial appendage, which showed resemblance to the cells of the atrio-ventricular conduction system. These cells form the sino-auricular node (node of KEITH-FLACK).

The node has a prolonged shape and extends caudally to the right from the angle between the recess of the vena cava superior and the right atrial appendage to approximately the middle of the sulcus terminalis (KOCH 1922, JAMES 1961). The cross-section is 2 × 3 mm, the length varies from 15-30 mm, while the shape also varies (i.e. tuberous horseshoe). The node contains much connective tissue and is difficult to distinguish microscopically from the surrounding cardiac muscle tissue. It is capable

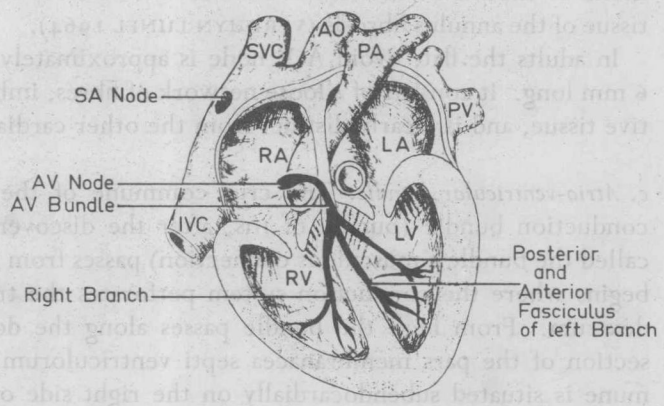

Fig. II-1.
The conduction system of the heart.

of generating by itself depolarisation waves which propagate throughout the cardiac muscle and cause contractions. For this reason the S-A node is called the 'pacemaker'.

These contraction waves diverge over the atria, but whether the conduction occurs by special conduction tissue is not yet clear. Some researchers believe they have proved the existence of special conduction bundles to the left atrium (TANDLER 1913, BACHMAN 1916) and the A-V node (THOREL 1910). The 'specific' tissue however is difficult to distinguish from its surroundings. Other investigators therefore believe that these bundles do not exist, but do not exclude the possibility of physiological pathways (LEV 1964).

The depolarisation wave diverging over the atria cannot reach the ventricles directly because of the annalus fibrosus between the atria and the ventricles. The transition to the ventricles occurs by means of the

atrio-ventricular conduction system. The 'musculous connection' between the atria and the ventricles, which forms a part of this system was demonstrated in human beings in 1893 by HIS.

b. Atrio-ventricular node. This specific group of heart cells was found by ASCHOFF and TAWARA in 1905. The atrio-ventricular node (node of ASCHOFF-TAWARA) is situated in the septum on the boundary between the atrium and ventricle, just superiorly to the pars membranacea septi and inferiorly to the base of the septal leaflet of the tricuspid valve. The proximal end of the node lies a few millimeters (± 6 mm) medioventrally to the recess of the coronary sinus, the distal end perforates the trigonum fibrosum dexter, where the node passes into the crus commune of the atrio-ventricular bundle. The node is situated against the tissue of the annulus fibrosis (VERDUYN LUNEL 1964).

In adults the flat, ovoid A-V node is approximately 3 mm wide, and 6 mm long. It consists of a loose network of fibres, imbedded in connective tissue, and is clearly distinct from the other cardiac muscle cells.

c. Atrio-ventricular bundle. The crus commune of the atrio-ventricular conduction bundle (bundle of HIS, after the discoverer, who in 1893 called the bundle a musculous connection) passes from the A-V node and begins where the conduction system perforates the trigonum fibrosum dextrum. From here the bundle passes along the dorsal and inferior section of the pars membranacea septi ventriculorum. The crus commune is situated subendocardially on the right side of the septum and extends to the left apically in the septum, whereupon it bifurcates into a right branch (crus dexter) and a left branch (crus sinister).

From the A-V node to the ventral boundary of the crus sinister the band-shaped crus commune is approximatively 8-10 mm long and 2-4 mm wide in adult. The bundle is constructed compactly from specific conducting cells and is surrounded by connective tissue.

d. Right and left branch. The *right branch* first extends on a line from the crus commune towards the apex. The bundle, which is round and surrounded by connective tissue, lies deeper in the muscle of the septum ventriculorum than the crus sinister. Apically to the base of the musc. Lancisii the crus dexter approaches closer to the surface, after which it leads sub-endocardially to the trabecula septomarginalis where arborisation occurs. The final transmission of the impulse to the cardiac muscle cells takes place by means of small branches.

The *left branch* bends to the left dorsally from the origin of the crus dexter. The bundle reaches the left part of the septum ventriculorum via the inferior section of the septum membraneceum under the attachment of the valvula semilunaris posterior aortae. The flattened bundle, surrounded by connective tissue, extends sub-endocardially and divides in a fanlike manner in the superior third part of the septum into anterior and posterior fasciculi which pass apically into smaller branches near the trabeculae at the anterior and posterior papillary muscle.

e. Purkinje cells. These cells, which were discovered in 1845 by PURKINJE, are distinguished from the other heart cells by their larger size, by having one or more nuclei with clear cytoplasm, by showing a halo around the nucleus and by containing few myofibrils, situated in the periphery of the cell (LEV 1964). Although Purkinje cells also occur in other parts of the conduction system, the crus dexter and sinister are composed entirely of Purkinje cells. Via the small branches of these bundles and the subendocardial network, the Purkinje cells form the last transition between the conduction system and the myocardial cells and effect the depolarization and subsequent contraction of the heart.

2. Vascularisation

The conduction system shows a wide variation in the vascularisation of the different parts (fig. II-2), especially with regard to the origin of the vessels supplying blood. The S-A node receives its blood in most cases – 70% according to LEV (1964) – via the atrial branches of the right coronary artery which reach the node ventrally and laterally. In the other cases the S-A node is vascularized by branches originating from the left or even both coronary arteries.

The A-V node is supplied with blood by an artery branch to the fibrous septum. This branch originates in most cases from the right coronary artery, just before this forms the posterior descending branch. In the remaining 10-20% of the cases (JAMES and BURCH 1958, LUMB and SINGLETARY 1962, LEV 1964) the septal branch originates from the circumflex branch of the left coronary artery or from both coronary arteries. The septal branch forms anastomoses with the anterior descending branch of the left coronary artery.

The crus commune and the first parts of the crus dexter and sinister are likewise supplied with blood by the septal branch, while they also receive blood from the anterior descending branch of the left coronary

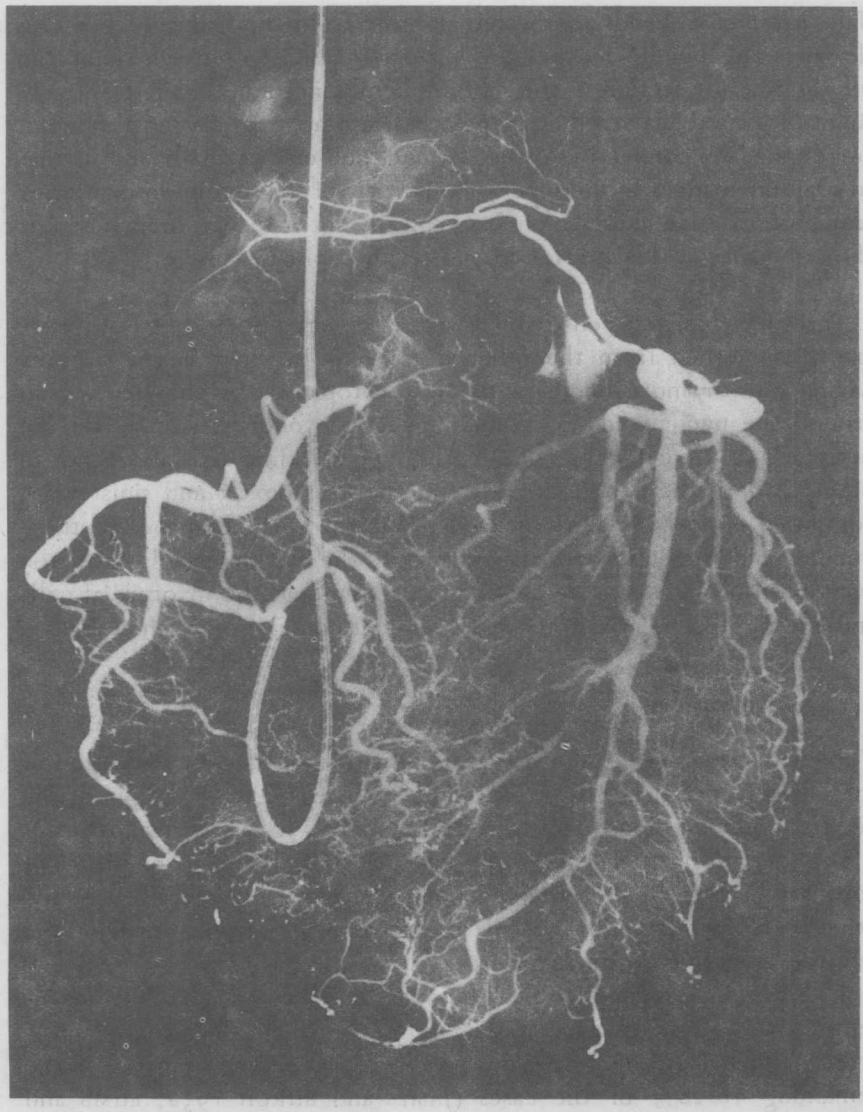

Fig. II-2. X-ray picture of coronary artery tree.
The vessels supplying the A-V node are arrowed. A bipolar catheter-electrode in the right ventricle is also shown. (By courtesy of DR. E. G. SOWTON.)

artery and the posterior descending branch of the right coronary artery, branches of which penetrate the ventricular septum.

In its further course the crus dexter receives blood especially from the vessels originating from the second perforating branch of the anterior descending branch.

In its further course the crus sinister receives blood from the anterior descending branch for the fasciculus anterior and the posterior descending branch for the fasculus posterior.

Of importance to the supply of blood to the atrio-ventricular conduction system are therefore the branches to the fibrous septum, which originate mostly from the right coronary artery and the perforating branches of the anterior and posterior descending branch, the branches of the anterior descending branch of the left coronary artery being of particular importance (JAMES and BURCH 1958).

B. Physiology

1. Pacemaker mechanism

The sequence in which the cardiac muscle fibres contract depends upon the point where the depolarization begins. This point must be the location of the pacemaker. Although many myocardial areas are capable of spontaneous activity, the pacemaker may be defined as that region of the heart possessing the highest rate of spontaneous rhythmicity (BULLARD 1963).

Investigations showed that the S-A node has the highest idio-frequency and normal sinus rhythm in man is approximately 70-80 beats per minute. Next to the S-A node the A-V node has the highest idio-frequency, so if the S-A node is eliminated atrio-ventricular rhythm of 50-60 beats per minute originates. The slowest rhythm is idio-ventricular rhythm, which is approximately 25-45 beats per minute. Continuous heart activity is guaranteed by the many automatic stimulus centres, situated especially in the normal conduction system of the heart; the frequency of contraction is slower as the site of origin of the impulse moves further towards the terminal branches.

The mechanism of the automatic depolarization is not yet completely know. An advance towards the explanation of this phenomenon was made when it became possible to deduce the potentials of a single cell by means of glass capillary micro-electrodes with a diameter smaller than 1 micron. Using this method it proved possible to demonstrate differences between the pacemaker cells and the other cardiac cells (fig.