Papers and Originals

Experience with Cardiac Pacemaking*

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The Tudor Edwards Memorial Lecture provides an opportunity to remember in gratitude the remarkable work Tudor Edwards did for thoracic surgery, and the introduction of the modern concepts that it led to in all forms of disordered intrathoracic function. Although he did little heart surgery, I feel that had he lived he would have entered this field enthusiastically. I therefore think that this is an appropriate occasion to report our experiences in Birmingham since 1958 in cardiac pacemaking, and the studies we have carried out during this time.

The problem of heart-block became especially important with the closure of ventricular septal defects by open heart surgery. Knowledge of the exact anatomy of the conducting fibres was incomplete, and they were liable to damage by the sutures. Lillehei (1957) reported on this, and heart-block had occurred in 12% of his cases. It was a very dangerous complication; if reversion to sinus rhythm did not occur spontaneously death was usual. Mr. L. D. Abrams, confronted by this problem at the Queen Elizabeth Hospital, asked Mr. Ashton to study the exact anatomy of the conducting tissue, and by careful histological serial sections he was able to identify the course of the bundle of His and the left and right branches down the septum (Ashton, 1960). The main bundle passes behind and below the septal defect. The larger and more important left branch then spreads out under the endocardium downwards and forwards on the left side of the septum. The right branch is a more definite tract lying under the endocardium at the lower edge of the defect. The sutures used to close the defect, or the trauma associated with them, was found to have interrupted the fibres and so caused the heart-block. As a result of this study it has been possible to avoid this complication by placing the sutures away from the immediate edge of the defect, and in his last 100 cases Abrams has had only one case of heart-block.

Meanwhile Zoll's (1952) work on external cardiac pacemaking had shown that electrical stimulation of the ventricles was feasible, and Weirich, Paneth, Gott, and Lillehei (1958) reported the successful pacemaking of surgically induced heart-block by bringing wires from the ventricle out through the chest wall to an external pacemaker. This proved a life-saving procedure, but the method was unsatisfactory except temporarily, because of the risk of sepsis along the wires, which were also vulnerable to fracture. Hudson, Lightwood, and Abrams therefore devised their method of inductive coupled pacemaking (Fig. 1). In this procedure the wires from the myocardium are led to a secondary coil under the skin of the chest wall. A primary coil lying over this on the outside is attached to the source of electrical impulses. The advantages of this method were immediately obvious. There is a minimum of apparatus within the body. With no discontinuity of the skin there is no track for the entry of infection. The external pacemaker can be regulated for rate and power, and can be replaced or turned off at will. Low voltages can be used, and are painless. Changing batteries is simple.

After experimentation in a dog the method was then used for human patients, and Abrams *et al.* (1960) reported their first three cases. These were in-patients with acquired heart-block: a woman of 56 having devastating attacks of Stokes-Adams seizure, a man of 60 with Stokes-Adams seizures, and a man of 66 incapacitated by chronic heart-block, congestive cardiac failure, and bronchitis. In each case complete success was achieved. The woman continued in active health until she died of carcinoma of the bladder two and a half years later. The second patient also died, four months after starting pacing,

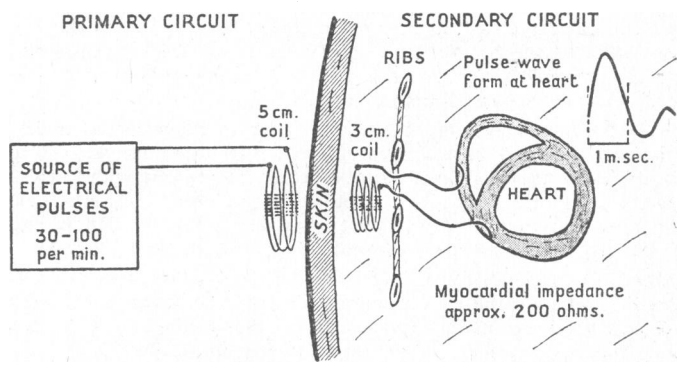

FIG. 1.—Diagram of the method of inductive coupled pacemaking. (Reprinted by permission of the *Lancet*.)

but at post-mortem examination he was found to have bacterial endocarditis on congenital bicuspid aortic valves, arising from a post-prostatectomy urinary infection, and also a small coronary thrombosis. The third patient, now aged 71, continues in good health more than five years later, having survived various vicissitudes of bronchitis, prostatectomy, and broken wires.

Since 1960 we have been able to study the haemodynamics of heart-block and also electrical and physical problems of the methods of artificial cardiac pacemaking. We have provided temporary or permanent pacemaking to 56 patients under my care, and some 30 or more patients under the care of my colleagues. Twenty-four other patients with various types of heart-block have not been suitable or have not needed continued pacemaking.

Clinical Use of Cardiac Pacemaking

The indications for pacemaking are becoming established in the management of heart-block and Stokes–Adams seizure. For other disorders of rhythm the possibilities are still under exploration.

1. Complete heart-block with the low cardiac output syndrome, showing symptoms of fatigue, mental deterioration, and breathless-

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ness, drug treatment having been ineffective and heart failure may be developing. Improvement can be predicted by studying the cardiac output at increased rates induced by an intracardiac electrode.

2. Stokes–Adams attacks are potentially dangerous. If not relieved by isoprenaline, steroids, etc., they can be prevented by cardiac pacemaking. They may be temporary, due to an unstable state of conduction, or during the change from partial to complete heart-block. There then may be recovery of normal sinus rhythm. In these cases a period of temporary pacemaking only may be needed. In complete heart-block Stokes–Adams attacks may still occur, due to cardiac asystole or rapid ventricular arrhythmias. These may need permanent pacemaking. With occasional Stokes–Adams attacks and sinus rhythm between them, pacemaking at a slower rate will afford protection, the artificial rhythm being available if asystole occurs. This, however, may not be without its complications, particularly if parasystole occurs—that is, if the pacemaking impulse follows a normal beat with a risk of provoking ventricular fibrillation. Experimental work is proceeding to design a new pacemaker which will be under automatic control so that it functions only during periods of total block.

Acute coronary thrombosis is sometimes complicated by heart-block, and the resulting low cardiac output adds additional damage to the circulatory insufficiency. The ventricular rate may indeed be quite fast and the block shown only by the E.C.G. Cardiac pacemaking is effective in overcoming this, and in many cases there is a return to sinus rhythm after hours or days, when the early disturbance of the infarction has partly subsided. The method can be life-saving.

3. Atrial flutter can occasionally be persistent and unresponsive to the usual medical treatment with digitalis, quinidine, and propranolol. External cardioversion has been used for these cases, but we have employed an internal atrial electrode, so giving a more elegant and less violent method of inducing a return to sinus rhythm, especially when the continued tachycardia has led to ventricular exhaustion. The electrode can also be kept in position for a time and be available should relapse occur.

Ventricular tachycardia due to one or more ectopic foci of excitation can also lead to a dangerous state. If unresponsive to drug treatment it may be possible to capture the rhythm with cardiac pacemaking, often at a fast rate but usually slower than the ectopic rate, so restoring a slower beat with improved circulation and frequently with permanent restoration of sinus or nodal rhythm.

There is evidence also (Cobbold and Lopez, 1965) that by pacemaking with a double pulse and critical timing one can slow the tachycardia due to multiple ectopic foci. This method has now been used successfully, and reported on by Bayley and Lightwood (1966).

Haemodynamic Effects of Cardiac Pacemaking

Haemodynamic studies have been undertaken on many of my patients in association with Professor Arnott's department, and many catheter studies have been made by Dr. Segel and others. The first study of the improvement in cardiac output by pacing the heart in our series was reported by Abrams *et al.* (1960). Hudson (1962) reported further studies on the cardiac output and intravascular pressures in complete heart-block. Segel, Hudson, Harris, and Bishop (1964) described a further study of the circulatory effects of electrically induced changes in ventricular rate at rest and during exercise in complete heart-block.

It is evident that the idioventricular bradycardia of complete heart-block results in a low fixed cardiac output. The pulse pressure is greatly increased, and there is evidence of arteriolar dilatation. The output can be achieved only by increasing the stroke volume. Enlargement of the heart occurs, and sooner or later cardiac failure supervenes.

By increasing the heart rate at rest the cardiac output increases and reaches, on average, its highest level, between 70 and 83 beats per minute, and is restored to normal (Fig. 2). A still faster heart rate produces no substantial rise in cardiac output, and in 6 of the 14 patients studied there was a fall. The stroke volume falls as the rate increases, the pulse pressure in the brachial artery is reduced but the mean pulmonary intravascular pressure remains the same, though again the pulse pressure becomes narrower. The pulmonary wedge pressure remains unchanged in most cases and provides adequate filling pressure for a shorter diastolic filling-time. In three subsequent patients with exceptionally high wedge pressures of 40–50 mm. Hg we observed a dramatic fall with pacemaking. The oxygen uptake rises significantly from the idioventricular rate up to 70 to 83 beats per minute.

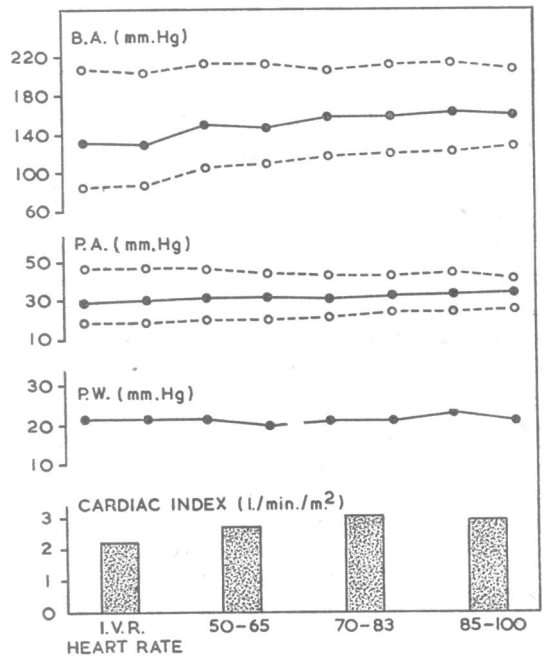

FIG. 2.—Haemodynamic effects of cardiac pacemaking in complete heart-block. Average values in 14 patients studied, showing brachial-artery pressure—systolic, diastolic, and mean; pulmonary-artery pressure and mean; and pulmonary wedge pressure. The blocks show the cardiac output at idioventricular rate and at electrically stimulated rates from 50 to 100. At the idioventricular rate the cardiac output of 2.2 l./min./m.² is considerably below normal, even allowing for the average age of 60; also the high pulmonary-artery pressure-mean of 30 mm. Hg, and pulmonary wedge-pressure-mean of 20 mm. Hg, and the wide pulse pressure are shown. (Reprinted by permission from the *Journal of Clinical Investigation.*)

Our data controvert the suggestion of Penton, Miller, and Levine (1956) that the slow rate is beneficial and protective to the myocardium. In many cases the fibrosis in the septum causing the heart-block is often minimal, and the improved circulation produced by pacemaking improves the heart failure and promotes better metabolic activity of the heart itself.

Observations were also made during exercise at a steady rate on a bicycle ergometer in the supine position (Fig. 3). At idioventricular rate the cardiac output increased from an average resting value of 2.2 litres per minute per metre² to 3.0/l./min./m.,² but this response, though significant, is much less than normal. There was an average increase of heart rate of only 5 beats per minute, and the increase in cardiac output was achieved by an increase in the stroke volume. The average rise was from 65 to 78 ml./m.² During exercise at electrically stimulated rates, however, the patients were able to perform more work, as judged by the oxygen intake. There was a significant rise in cardiac output from rest to exercise at a heart rate between 73 and 94 beats per minute. The average cardiac output increased from the resting value of 2.9 l./min./m.² to 4.0 l./min./m.², which was highly significant.

Regional blood-flows have also been studied in patients with heart-block. It had been observed that many of these patients had impaired renal function at idioventricular rates, and were clinically improved by cardiac pacemaking. Aber (1965) has

studied six patients and found the renal response to pacemaking to be variable (Fig. 4). Where renal function is poor considerable improvement occurs with pacemaking. In other patients with little impairment of function there is not much change. In three patients the oxygen uptake of the kidneys was measured by Bayley and Segal and did not alter significantly, nor did the renal fraction of cardiac output.

Splanchnic blood-flow has been studied by Bayley and Segel on 15 patients. The cardiac index, the splanchnic oxygen uptake, and the splanchnic blood-flow were measured. It was found that an increase of heart rate led to increased cardiac output and total body oxygen uptake and splanchnic blood-flow. But at the same time there is no corresponding increase in splanchnic oxygen uptake in spite of the raised splanchnic blood-flow. There is indeed no change in the splanchnic fraction of the cardiac output.

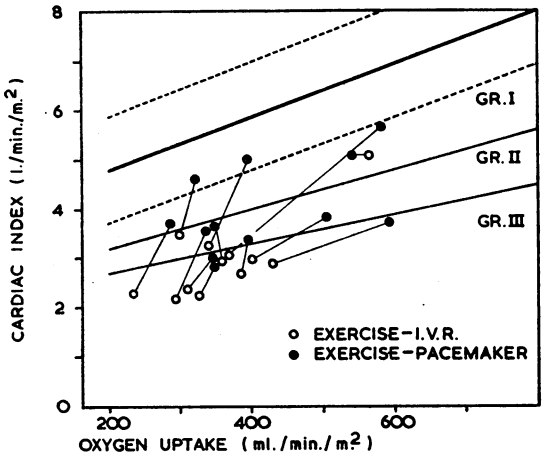

FIG. 3.—Effect of pacemaking on cardiac output at rest and exercise. The individual values of the cardiac index are plotted against oxygen uptake during exercise. The thick line shows the predicted normal response with its 95% confidence limits shown by the interrupted lines. Also shown are three arbitrary grades of impairment of cardiac output in response to exercise—mild ((grade I), moderate (grade II), and severe (grade III). The open circles represent the exercising values at idioventricular rate, and the closed circles are those during pacemaking at 75–85 beats per minute. The values for cardiac output during idioventricular rate are all grossly impaired. During pacemaking there is a substantial improvement in every case, except one with congenital heart-block. Not only are the grades of impairment less, but the patients are able to exercise more, as judged by the greater oxygen uptake. (Reprinted by permission from the *Journal of Clinical Investigation*.)

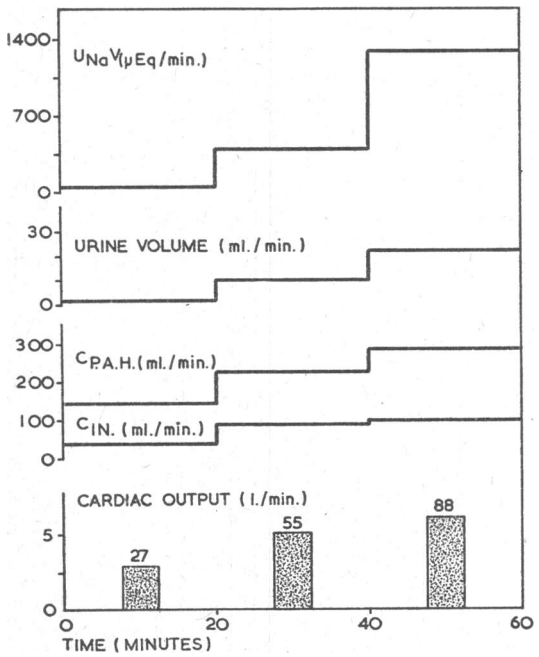

FIG. 4.—Response of renal function to cardiac pacemaking. The values for one patient in whom there was marked improvement in renal function (as a result of pacemaking). The urinary sodium excretion, urine volume, and clearances of para-aminohippuric acid and inulin are all considerably reduced and return nearly to normal with pacemaking.

It seems, therefore, that despite an increase in cardiac output there is no alteration in the relative regional blood-flow, either to the kidneys or to the splanchnic vessels. Nor does the oxygen uptake in these regions increase with the artificially increased heart rate. We are in process of studying regional blood-flows and oxygen uptake in other areas. In the femoral vessels the flow increases but not the relative oxygen uptake. We are also studying the cerebral circulation. It may prove to be that the observed and significant rise in total oxygen consumption is evidence of the beneficial effect of pacemaking the abnormally slow heart.

Methods of Cardiac Pacemaking

Many methods of cardiac pacemaking have been devised by workers in all parts of the world. Two fundamental routes are available for electrical stimulation of the myocardium. One is by implanting wires into the wall of the myocardium. This has to be done by open thoracotomy. Abrams (1965) has been using braided stainless-steel wires armed with an atraumatic needle, which is used to take three bites of the myocardium in an area of about 1 by 0.5 cm. This area and the adjacent centimetre of insulated lead are then covered with a Teflon felt patch sutured to the heart. It is essential to avoid any local fixation-point where movement is concentrated, as this is apt to lead to fatigue fracture. Otherwise we have found stainless-steel wire suitable material for long-term pacemaking. With a pacemaking impulse of biphasic wave-form the sum of the positive and negative waves is the same: thus electrolytic effects at the electrodes are minimized.

The second method is by introducing an electrode into the right ventricle through a vein—the median basilic or external jugular is most often chosen. It is passed under fluoroscopic control into the apex of the right ventricle, and can be embedded there, its effectiveness being controlled by electrocardiographic monitoring. This method has the simplicity of avoiding the hazards of thoracotomy, as well as being possible quickly and in emergency. It has the disadvantage of a foreign body in the veins and heart, though remarkable tolerance to this has been experienced. Any infection must be energetically controlled to prevent septicaemia. Valvular disease is probably a contra-indication for fear of bacterial endocarditis. It is obviously very suitable for temporary pacemaking, and during cardiac catheterization studies when the benefits of continued pacemaking are being assessed.

The method of electrical supply has been much more controversial. I have already referred to the inductively coupled coil method which we have developed in Birmingham and found both efficient and satisfactory, and the reasons why. The internal coil consists of a thousand turns of 38-gauge copper wire enclosed in silicone rubber, and it is placed under the skin on the front of the chest wall. When the wires are led direct to the myocardium they are easily passed through an intercostal space. When an intracardiac electrode is used and it is desired to make this permanent it is passed through an opening in the external jugular vein at the root of the neck and joined to the wires of the coil, which is positioned subcutaneously a little below the clavicle, a coil of wire being arranged to allow for movement of the arm and muscles without it pulling on the electrode. The second wire is stitched into the chest wall close by.

The external coil is secured outside the chest over the position of the internal coil. The power is quite adequate for this not

to be critical, and any skin movement does not interfere with the induced current. The pacemaker itself now used can be carried in any simple bag slung from the shoulder or waist. It is powered by a single U2 battery, obtainable anywhere, which normally lasts a month, is cheap, and readily replaced in a moment (Fig. 5). All patients are supplied with two units so that they have a spare and can change to the second unit at any time. An audible tick can be switched off when confidence is gained. The rate can be controlled by a knob and varied by the patient to suit his activities and personal feelings.

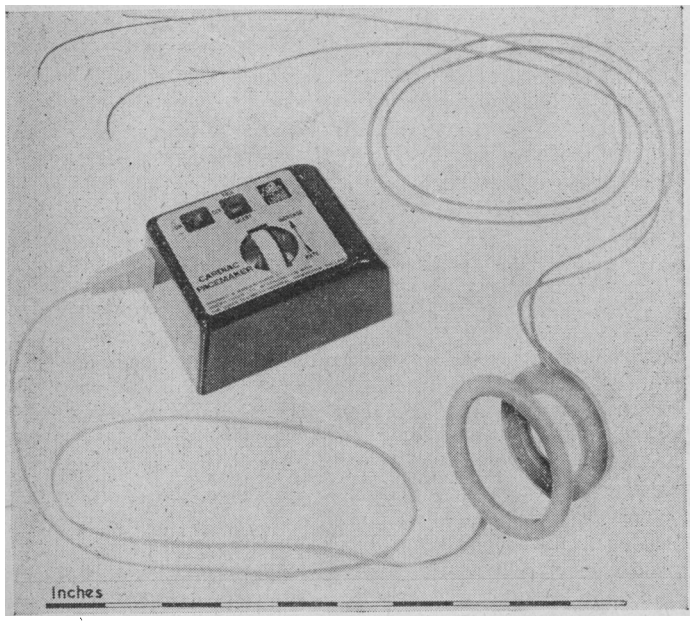

FIG. 5.—Inductive coupled-coil cardiac pacemaker. Pulse generator, showing coils and internal wires.

During the past five years we have, of course, had our experience of faults. Broken wires have been the most troublesome, but with development of the technique these have become rare. At first we had some faulty coils. We also used a Teflon covered coil, and effusion and infection round this occasionally caused trouble. Now the silicone-rubber-covered coil is proving trouble-free and efficient. The new coils now being produced carry a far superior electrode lead, which is comprised of a triple helix of stainless steel. This is at least 300 times more resistant to fatigue fracture. An intracardiac electrode is also being developed of similar construction. By using a plug-and-socket connexion it is free for introducing a wire stylet, which can aid the initial positioning before being withdrawn, leaving a completely flexible lead from the coil to the right ventricle.

Clinical Features and Illustrative Cases

Since February 1960 I have had under my care 56 patients (37 males, 19 females) requiring temporary or permanent pacemaking. Their average age was 57 years, ranging from 7 to 78. Of those with permanent pacemaking 28 are still alive, and the period of pacemaking has been up to five and a half years. They have been relieved of Stokes–Adams attacks, and of the effects of the low output state during the five and a half years from February 1960.

A man of 66 came into the Queen Elizabeth Hospital in 1960 with complete heart-block—atrial rate 75, ventricular rate 40. He had been short of breath for five years, but got worse one month before admission and was in congestive heart failure. There was also severe bronchitis, his blood-pressure was 210/90 mm. Hg, and a soft systolic murmur was heard. An intracardiac electrode was passed, and he was paced at 70/min. There was immediate improvement; the heart failure resolved and his bronchitis improved. A week later, at thoracotomy, wires were sutured to the heart from a subcutaneous coil and inductive pacemaking at 70/min. was maintained. He has kept alive and well since, though with some difficulties. The wires have broken (resulting in Stokes–Adams attacks) and have been replaced finally by an intracardiac electrode. He developed retention of urine and needed a prostatectomy. He has had some further attacks of bronchitis. Although advised not to do so he has driven his car. He has fished and led an active life.

A woman aged 46 in January 1965 had had precordial pain and breathlessness for two years. On admission her pulse was 30/min. and B.P. 210/80. Electrocardiograms showed atrial fibrillation and complete heart-block. Isoprenaline was tried, but it provoked Stokes–Adams attacks. An intracardiac electrode was passed and the heart paced at 80/min., with relief. Cardiac catheterization showed a cardiac output of 2.0 l./min./m.^{2} at her idioventricular rate of 35, but it rose to 3.1 l./min./m.^{2} at 66 and to 3.6 l./min./m.^{2} at 86. A subcutaneous coil with wires to the ventricles was therefore inserted at thoracotomy, and pacemaking has been continued successfully since, with complete relief of her symptoms.

A man aged 42 in 1960 showed the effect and limitation of the low-output syndrome of heart-block. He had had diphtheria when aged 28, and subsequently developed a slow pulse. He gained entry to the Police Force, but was subject to pains in the limbs, dizzy spells, and general weakness, and could not be employed "on the beat." His pulse had been about 50, but in 1960 it became 30, with a blood-pressure of 200/70; lassitude and insomnia were increasing. He developed chest pain on exertion. Catheter studies showed that on exercise at his idioventricular rate he could increase his cardiac output from 5 to 6 l./min., but his pulmonary-artery pressure also rose and the pulmonary wedge pressure reached 31 mm. Hg. With pacemaking at 70 beats per minute his cardiac output rose to 9 l./min., and on exercise his pulmonary wedge pressure remained at 15 mm. Hg. He has been pacemaking for the subsequent five years, and now leads a normal life, including gardening.

Acute coronary thrombosis caused heart-block in five patients needing immediate pacemaking, all of whom survived. The extent of the myocardial infarct has no relation to the production of heart-block. Patients who have recovered after a period of temporary pacemaking may show minimal electrocardiographic changes subsequently, and little or no functional disability. Pacemaking is therefore always worth trying, but the result will naturally depend on the underlying cardiac state. It may, however, turn the scales at a critical stage after the infarction.

A man aged 55 in June 1961 collapsed with pain across the chest from a coronary thrombosis. The next day he had transient attacks of loss of consciousness. He was admitted to another hospital and found to have the symptoms of a low cardiac output and a pulse of 12/min. An E.C.G. showed complete heart-block with coupled ventricular ectopic beats. The effect of the coronary thrombosis and the low cardiac output made the situation desperate, and he was transferred to the Queen Elizabeth Hospital. Isoprenaline raised the heart rate to 40/min., but this was complicated by Stokes–Adams attacks. An intracardiac electrode was introduced, and he was paced at 75, with immediate improvement. After 24 hours his heart returned to sinus rhythm and the pacemaker was turned off; after a further five days the electrode was removed. He proceeded to make a good recovery from his coronary thrombosis, and there was no return of his heart-block, the P–R interval was 0.16 sec., B.P. 160/90, and sinus rhythm was maintained.

Chronic heart failure may follow prolonged heart-block, and be unresponsive to the usual medical treatments.

A man of 74 had been in such a condition for three years, with a pulse of 40, B.P. 150/70, and complete heart-block. There was obstinate oedema and severe shortness of breath. An intracardiac electrode was used to maintain a pulse of 80. Within a week the heart was reduced in size and the congestive failure relieved. The temporary catheter was then replaced with a permanent intracardiac electrode fixed to a coil, and the patient returned home; he was alive and well one year later.

Post-mortem examination of the heart in patients who have died has usually shown enlarged hearts of 400 to 600 g. Often there was only isolated fibrosis involving the interventricular septum immediately beneath the aortic valve and minimal

coronary atheroma. In other cases there was superadded acute coronary thrombosis, which evidently determined death in spite of effective pacemaking. One comes to appreciate that effective electrical stimulation of the myocardium does not necessarily produce adequate ventricular contraction if the myocardium is hopelessly ischaemic or fibrosed or if ventricular fibrillation supervenes.

We have thought that ischaemic heart disease was responsible for the heart-block in the majority of cases. Diphtheria was probably the cause in one case, and there was evidence of rheumatic heart disease in three cases, of aortic valve disease in two (one congenital bicuspid valves, one gross calcific stenosis), and in one girl of 7 whose heart-block followed successful operation for congenital pulmonary stenosis at another hospital.

Future Problems

Our experience has shown that many future problems may have to be overcome. The co-ordination of atrial and ventricular contractions would obviously help the haemodynamic response to pacemaking by having the benefit of atrial systole to give proper ventricular filling before its systole. A suitable auricular trigger is electronically feasible, but would have to include devices to protect against auricular fibrillation or an inadequate P-wave stimulus.

The management of cardiac arrhythmias is being improved by pharmacological advances. Our studies suggest that their control by pacemaking methods may often be more convenient and be associated with less commotion than with external methods, at the same time lower voltage being used and provision made for continuous or relapsing disturbances.

My colleagues Dr. Davison and Dr. McIlveen (Small *et al.*, 1966) have developed a method of inducing circulatory arrest with controlled tachycardia or ventricular fibrillation, using a pacemaker with an intracardiac electrode at rates of 90 to 240 per minute. This method is being developed to assist the neurosurgeons in obtaining an arrested circulation for intracranial vascular surgery under hypothermia.

In conclusion, published reports reveal that many workers are intensely interested in this exciting and life-saving field of therapeutics where medicine, surgery, and electronics all combine. Not only have lives been saved but the depressed, vegetable existence of those with low cardiac output has been restored to alert and healthy activity.

Summary

Heart-block may lead to severe disability as a result of the low cardiac output. Haemodynamic studies have shown the relation of the fixed slow heart rate to cardiac output, and that increasing the rate improves the output and consequently improves regional renal and splanchnic blood-flow. It also seems probable that the better circulation also relieves heart failure and promotes better metabolic activity of the heart itself.

Stokes–Adams attacks are potentially dangerous, and, though sometimes relieved by isoprenaline, in many cases they are prevented only by continuous cardiac pacemaking.

Electrical stimulation of the heart has been used for chronic and acute forms of heart-block. For temporary and emergency use an intracardiac electrode can be introduced through a superficial vein. For permanent use either an intracardiac electrode or wires attached to the ventricle can be employed, and if joined to a subcutaneous coil an external pacemaker can be used to induce a current in the coil. The advantages of having the external pacemaker are described—it can be regulated for rate and power and can be replaced or turned off at will. Low voltages can be employed, and are painless ; changing batteries is simple. There is a minimum of apparatus inside the body, with no discontinuity of the skin.

Experience of the inductive method of cardiac pacemaking in 56 patients is described, covering a period of five and a half years ; 28 of them are still alive.

I acknowledge with pleasure the assistance given me by many colleagues and the investigations carried out by them on my patients. Dr. W. A. Hudson did much of the original work, and he and Mr. R. Lightwood devised the inductively coupled cardiac pacemaker. The clinical care has been carried out by Dr. Hudson and Dr. T. J. Bayley while they have been my senior medical registrars. I have been singularly fortunate in my ward sister, Miss Huckerby. Dr. N. Segel and Dr. Bayley have carried out the cardiac catheter studies, and Professor Arnott's department has been most helpful with many of the investigations. The electrical apparatus has been made by Messrs. Joseph Lucas Ltd. to the design of Mr. Lightwood, who has been an inventive, interested, and patient electronics engineer. Most of the surgery and much of the initiative has come from Mr. L. D. Abrams, and I acknowledge his skill and co-operation. Mr. N. J. Shah has also done some of the operations.

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