

AN ELECTRICAL ARTIFICIAL PACEMAKER FOR STANDSTILL OF THE HEART*

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DURING A RECENT INVESTIGATION^{1, 23} of the use of general hypothermia for experimental intracardiac surgery, it was observed that complete standstill of the heart occurred quite frequently at very low body temperature. It was also noted that application of a stimulus, whether electrical or mechanical in character, to the region of the sinoauricular node resulted in the production of normally appearing expulsive beats.

An attempt was made to develop a technic whereby frequent regular electrical stimuli of required strength and character could be applied to the sino-auricular nodal area to act as an artificial pacemaker, which might permit control of heart action for prolonged periods after cardiac arrest.

In this study such an artificial pacemaker has been used for cardiac arrest in dogs at low body temperature. Our interest has been extended to the application of this principle in the control of heart action at normal body temperature. The only type of cardiac arrest which it was thought would provide a situation whereby artificial pacemaker activity could be demonstrated was

that due to cessation of impulse formation from the sino-auricular node without the severe conduction changes occurring in postmortem or terminal hearts. Preliminary unsuccessful attempts to produce artificial heart action in postmortem dog and rabbit hearts supported this view.

In the development of a technic to produce experimental cardiac arrest at normal body temperature, attempts were made to locally obliterate the normal sino-auricular nodal action. Such devices as excision, trauma, infiltration with chemicals and the application of cold solutions proved, as reported by Sherf,² to be difficult procedures and unsatisfactory for this study.

Rothberger and Winterberg,³ in 1911, demonstrated that right vagus nerve stimulation in the neck of a dog usually produced standstill of the heart. It is described as rather selective inhibition of the sino-auricular nodal activity with little or no effect on conduction.⁴ This, then, would provide a brief standstill but one of sufficient duration to permit the introduction of beats from an artificial electrical stimulus. It was thought also that this would simulate most closely the standstill of the heart occurring clinically during operative procedures.

Pratt,⁵ in 1924, stated that the pacemaker is governed, at least in part, by the chemical content of venous blood returning to the right auricle. Gesell,⁶ in 1944, reported that increasing the CO₂ content decreased the pH of perfusion fluid around isolated frog and turtle hearts and made the pacemaker

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more sensitive to acetylcholine, and likewise, vagal inhibition. Recently Sloan,⁷ using afferent vagal stimulation, has confirmed this by more easily producing cardiac standstill in animals in a hypoxic, hypercapnic state. Nathanson,⁸ in 1932, by carotid sinus pressure, was able to produce in humans standstill lasting five to 15 seconds; this did not occur if he first gave atropine.

HISTORICAL

As early as 1862, Walshe⁹ suggested faradic stimulation of cardiac sympathetic nerves to restart a stopped heart. Barber and Madden¹⁰ studied all operative cases of cardiac standstill reported up to 1945 and noted that in 143 cases cardiac massage with or without intraventricular injection of adrenaline had been used. Only 48 cases, or 33 per cent of the total group, survived and showed no ill effects.

In 1932, Hyman¹¹ suggested that the effect of adrenaline injection was unspecific and was actually due to the injecting needle setting up an irritable focus which produced an extra systole and stimulated beat formation from the sino-auricular node. To try this postulation he actually constructed an electrical needle which he inserted into the right auricular wall of animals to act as a pacemaker. He used this in cardiac arrest in guinea pigs brought about by suffocation, with some apparent success. No further study of artificial pacemaker activity has been reported. Sweet¹² restarted two human hearts during operation by applying electrical current to the sino-auricular nodal region, with survival.

Beck and Mautz¹³ have reported the occurrence of standstill of the heart while using alternating currents to overcome ventricular fibrillation during operation, for which they used adrenaline and massage.

With these facts in mind, our attention has been directed to the study of the problem of cardiac arrest to determine if the use of an electrical artificial pacemaker in resuscitation would be of value. In many years

the only approach to this problem has been that of cardiac massage and intraventricular injection, with poor survival rate.

METHODS

Twenty-four mongrel dogs of medium size (6 to 12 Kg.), and nine rabbits (2 to 3 Kg.) were used in this investigation.

The studies at low body temperature included 11 dogs cooled in refrigerated blankets* by a technic described in detail in a previous report.¹⁴ The animals were given sufficient intravenous Pentothal sodium anesthesia to control shivering. By this means the rectal temperatures were reduced to between 15.8° C. and 21.5° C., during which range either complete standstill or extreme slowing of the heart occurred. At this time the chests were opened by resection of the right fourth rib and pacemaker studies commenced.

At normal body temperature observations were made on 13 dogs and nine rabbits. The animals were given sodium Pentobarbital intravenously and intubated. The chests of the dogs were opened by resection of the fourth right rib, whereas in the rabbits a sternum-splitting approach was used, with resection of the third to sixth ribs on the right side. The pericardium was incised and normal heart action observed. Standstill of the heart was then produced by applying a tetanizing current to the right vagus nerve through a separate incision in the neck.

Pacemaker Electrodes. Two main types of electrodes were used in the studies at both low and normal body temperature:

A. A two-point focal electrode was usually used. Two sites of application, one externally and the other internally, are described later. The stimulating metal tips were separated by a distance of 1 mm. at the end of an eight-inch plastic-insulated hollow metal tube. These tips were connected by insulated wires to the stimulat-

* Therm-O-rite Products, Ltd., Buffalo, N. Y.

ing device. The intravenous electrode was modified so that it could be included in a No. 12 French intracardiac hard rubber catheter or a plastic tubing of the same size.

B. A single-point stimulating electrode similar in appearance to the two-point electrode, but having only one stimulating tip placed in the region of the sino-auricular node, was also used. The second contact

second or third interspace on the right side just large enough so that the electrode was gripped firmly in the chest wall. The rod then passed deep in contact with the right mediastinal pleura to the pericardium. Here an incision just large enough to admit the electrode was made so that it was fixed against the sino-auricular node region (see Fig. 1).

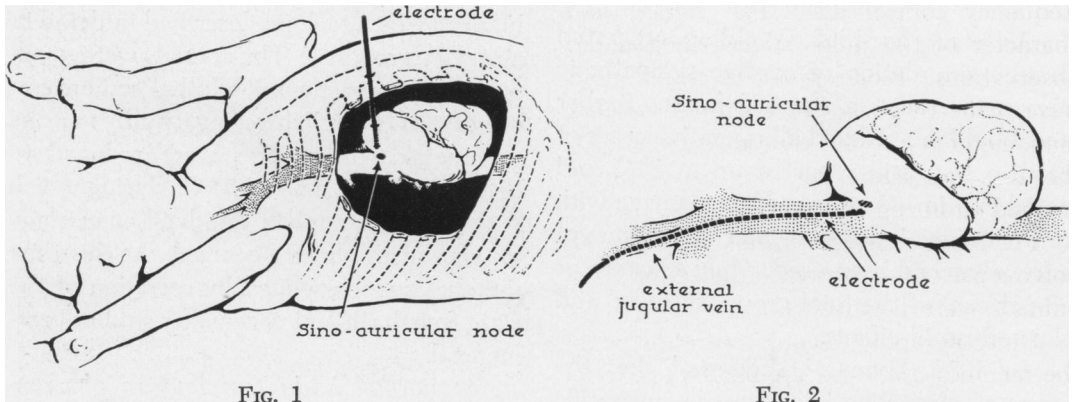


FIG. 1.—The two point artificial pacemaker electrode in external contact with the sino-auricular node after passing through separate incisions in chest wall and pericardium.

FIG. 2.—The intracardiac application of the pacemaker electrode to the deep surface of the sino-auricular node after being inserted through the external jugular vein to lie in the superior vena cava.

consisted of an indifferent electrode clamped onto the muscles of the chest wall incision. Though not as efficient as the two-point electrode, it did provide an easy method of determining when the stimulus was delivered, for a twitch occurred in the muscle of the chest wall at approximately the same time that the impulse reached the sino-auricular node.

Sites of Application of the Artificial Pacemaker Electrodes. The proper location of the pacemaker was taken to be the junction of the superior vena cava with the right auricle, as described by Eccles¹⁵ in cats and Taussig¹⁶ in human beings.

Two approaches to the sino-auricular node were used:

1. External Application: By this method the electrode was inserted through a separate incision in the anterior end of the

2. The Intracardiac Application: To approach the pacemaker without opening the chest an electrode of the two-point type was made up in a tube the size of a No. 12 French hard rubber venous catheter. The electrode was inserted into the right external jugular vein, passed through the superior vena cava until the stimulating tip lay in intimate contact with the deep surface of the sino-auricular node at the junction of the superior vena cava and right atrium (see Fig. 2). This was further developed, and is pictured in Figure 4.

The electrical source was a Thyatron physiologic stimulator capable of delivering single impulses that could be easily controlled as to pulse pattern, pulse duration, pulse delay and frequency. A Grass Model 3C stimulator* was found to be satisfactory,

* Grass Instrument Co., Quincy, Mass., U.S.A.

but the desired electrical features were developed in a simplified circuit by J. A. Hopps, (National Research Council of Canada) and constructed into a portable model (see Fig. 3).^{*} Both monophasic and biphasic impulses could be delivered. Two means of delivery were used; one consisted of single impulses under foot pedal control, the other of impulses delivered automatically at a desired rate and regulated by a frequency control dial. The voltage and character of the pulse is described under observations. Blood pressure observations were made by means of a simple mercury manometer connected to a glass cannula in the femoral artery on one hand and a smoked drum on the other.

For blood pressure studies and those involving use of the intravenous electrode, the animals were heparinized.

Cinematographic records were made of the technics used and the results obtained.

OBSERVATIONS

A. At Low Body Temperatures: As the 11 dogs reached rectal temperatures between 15.8° and 21.9° C., cessation or extreme slowing of the heart occurred. In each of the 11 animals artificial expulsive beats could be produced by the application of the pacemaker electrode. The maximum rate that could be obtained was similar in the hearts that had stopped completely and those in which extreme slowing of the heart had occurred. At 21° C. the rate could be increased to an average maximum of 40 beats per minute. The rate decreased as the rectal temperature fell, and at 15.8° C. the average maximum possible was 26 artificial beats per minute.

The longest time during which artificial heart action was produced was 70 minutes. In one animal cooled to rectal temperature of 19.0° C. in which cardiac standstill occurred, controlled heart action was conducted for 30 minutes before spontaneous

heart action occurred, after which the animal was re-warmed to normal body temperature, having suffered no evident ill effects.

As in the studies at normal body temperature, best results were obtained by a single pulse type current lasting usually .002 of a second.

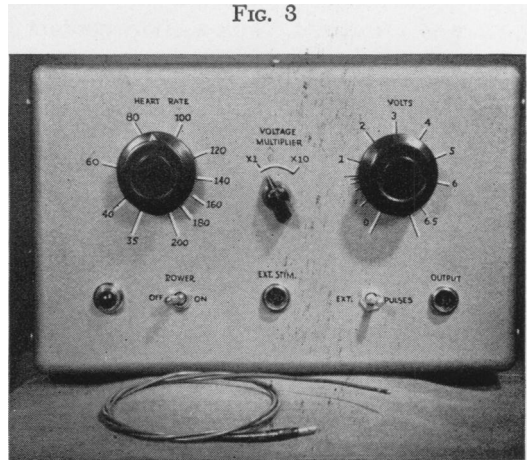


FIG. 3

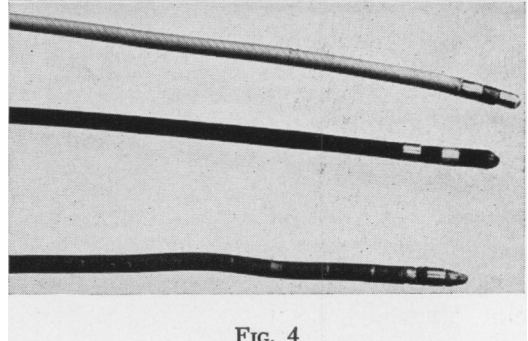


FIG. 4

FIG. 3.—A photograph of the portable artificial pacemaker developed by The National Research Council of Canada, Ottawa. The coiled intravenous electrode is shown in front of the machine.

FIG. 4.—Photograph of two types of intracardiac electrodes of the electrical artificial pacemaker developed by Electrical Division, National Research Council, Ottawa, Canada.

In two animals at low body temperature ventricular fibrillation had previously occurred. Defibrillation was carried out by application of alternating currents to the hearts in both cases, with disappearance of fibrillation and its replacement by cardiac arrest. After 17 and 12 minutes, respectively, of artificial heart action, spontaneous beats

^{*} Smith and Stone Co., Ltd., Georgetown, Ont., Canada.

FIG. 6

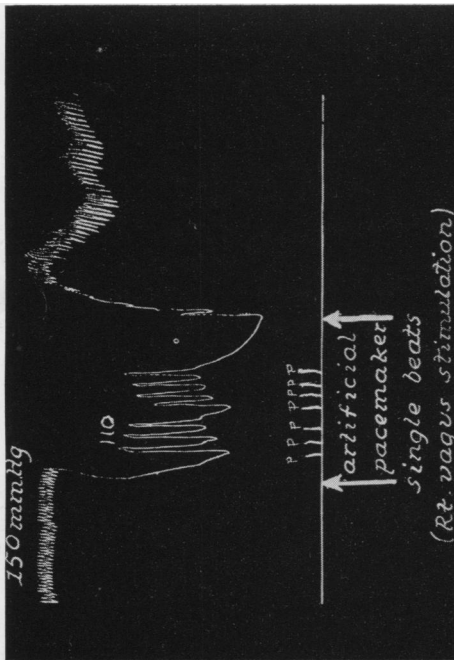


FIG. 5

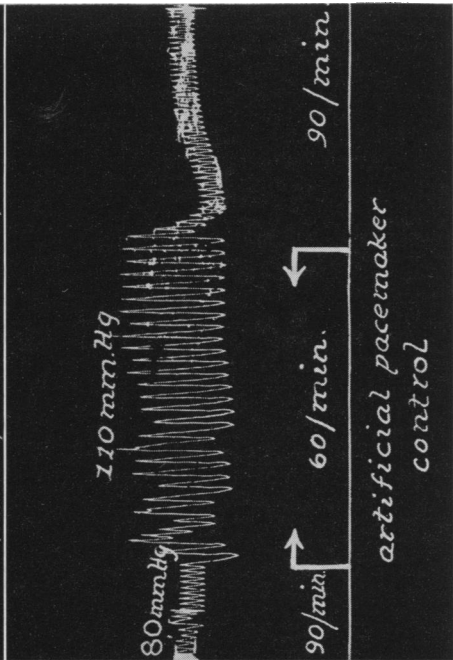
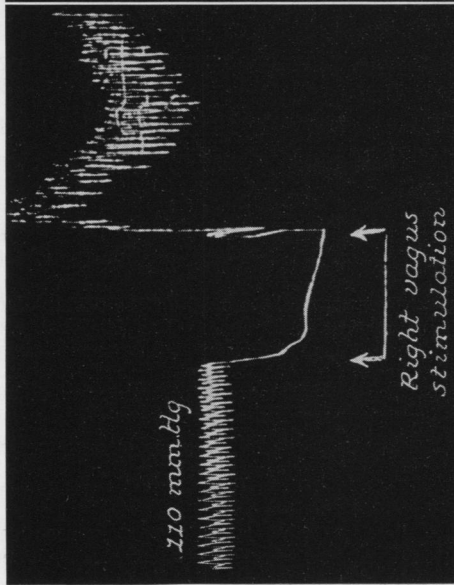


FIG. 8

FIG. 7

(Legends on opposite page)

reappeared. In one of these animals, good heart action continued and it was rewarmed to normal body temperature.

At low body temperature it was observed that the stimulating electrode did not have to be in contact with the sino-auricular node for the production of good beats; almost any area in the upper half of the right atrium sufficed.

B. At normal body temperature: Arrest of the heart was produced by right vagus nerve stimulation in the nine dogs and nine rabbits studied at normal body temperature. The standstill varied in length from four to 30 seconds in the dog and slightly longer, on the average, in the rabbit before the heart escaped the vagal influence and started to beat again.

When the heart stopped the blood pressure immediately fell to low levels, averaging 40 to 50 mm. Hg. (see Fig. 5). As the heart escaped and commenced beating, the blood pressure rapidly rose to a temporary level well above that before the standstill, because of the anoxia that had developed.

During this period of standstill of the heart, artificial beats could be produced in all animals. In the six dogs in whom blood pressure recordings were made, average rises to 110-140 mm. of Hg. from initial levels of 40-50 mm. Hg. occurred with each artificial beat (see Fig. 6).

FIG. 5.—Smoked drum record of effect on heart rate and blood pressure of stimulation of right vagus nerve of a dog in the neck by a tetanizing current.

FIG. 6.—A smoked drum record of the effect of single impulses applied to the S. A. node of a dog's heart in standstill from right vagus nerve stimulation.

FIG. 7.—A smoked drum record of the effect on heart rate and blood pressure of applying artificial pacemaker and right vagus nerve stimulation at the same time. Little or no fall in blood pressure is observed until the artificial pacemaker is stopped.

FIG. 8.—A smoked drum record of the effect on blood pressure and heart rate of applying the artificial pacemaker at 60 a minute to a heart beating 90 a minute spontaneously. Note increase in the pulse pressure and maintenance of the mean blood pressure. The artificial pacemaker completely controls the heart and inhibits the normal beat.

When both vagus stimulation and automatic pacemaker impulses were applied at the same moment, the latter prevented the usual fall in blood pressure. When the artificial control was turned off, a sudden drop in blood pressure due to the continuing vagal influence occurred (see Fig. 7).

In eight animals (five dogs and three rabbits), after repeated experimentation, the heart rate had dropped to slower than their usual normal rates (70 to 120 beats a minute). By artificial pacemaker regulation the heart action could be controlled at a faster rate up to 200 a minute (see Fig. 11), or at a slow rate down to 60 a minute (see Figs. 8 and 9). At the slower rate, pulse pressure was observed in all cases to be increased markedly by the increased time for filling. However, the mean blood pressure remained unchanged, due to the greater fall in diastolic pressure created by the longer time interval between beats. At the faster rate the pulse pressure decreased, but the mean blood pressure remained as high or in some cases much higher than the initial level before the artificial control (see Fig. 10). This appeared to be complete control of the heart beat, and immediately on cessation of the sino-auricular stimulation, the normal pacemaker took over spontaneously at the rate prior to artificial control. It is interesting to observe, as shown in Figure 10, that the heart rate and blood pressure rose after artificial stimulation to a level more closely approximating their normal. This was not a constant finding, but did occur on several occasions.

The experiment was then reversed, with the heart controlled completely by the artificial pacemaker at the normal or at a faster rate, and the right vagus was stimulated in the usual manner. Little or no decrease in rate or fall in blood pressure resulted from the stimulation of the nerve until the artificial control was shut off. With the continuing vagal influence, the blood pressure immediately fell to low levels (see Fig. 12). This was repeated as many as five times on

FIG. 10

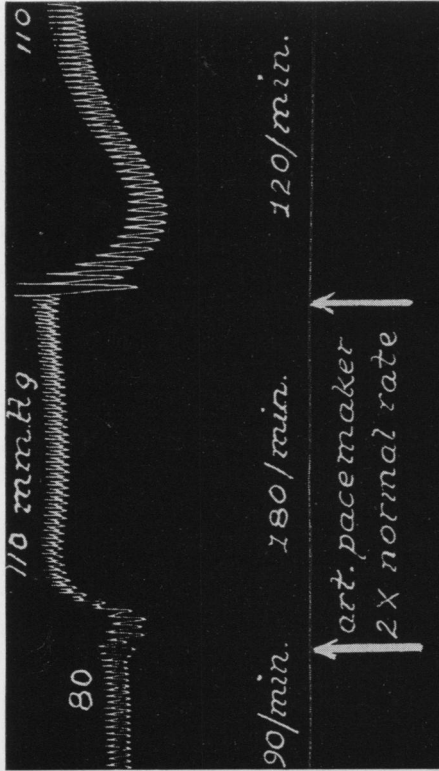


FIG. 9

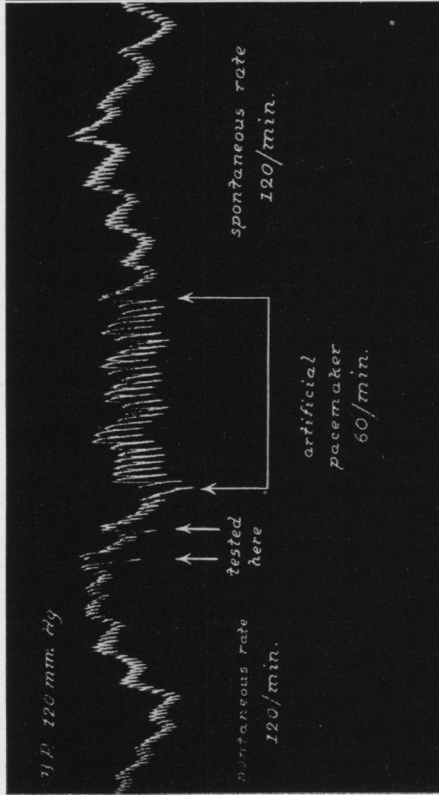


FIG. 12

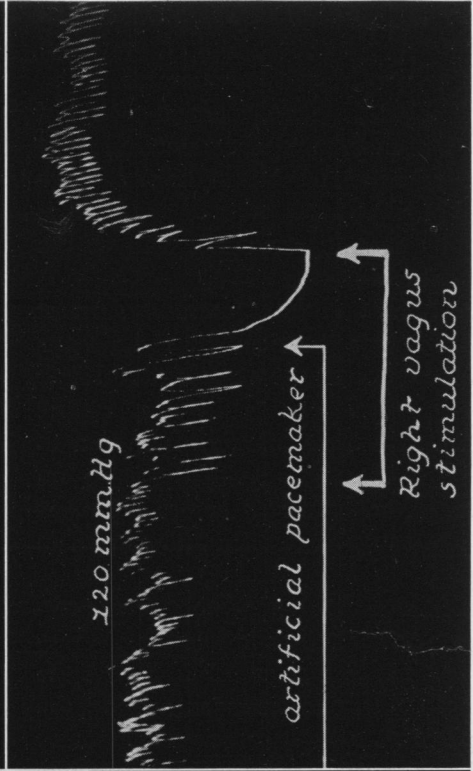
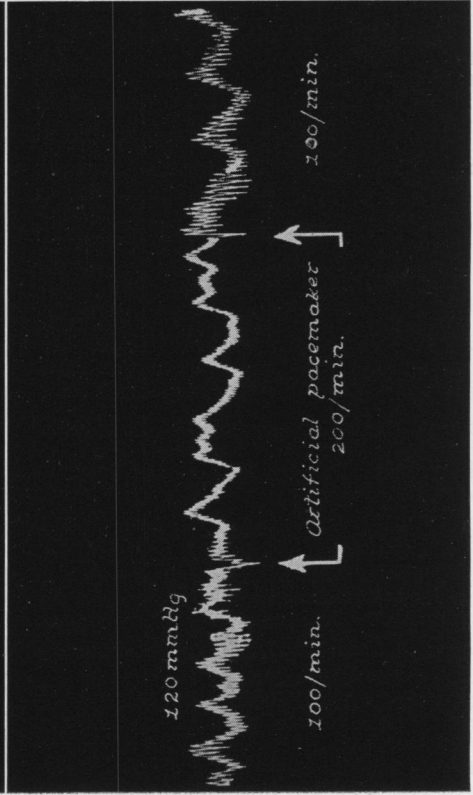


FIG. 11



(See legends on opposite page.)

the same animal and in ten different animals.

With the heart under complete artificial control, using the intravenous electrode, tests were carried out to determine the proximity to the sino-auricular node required for control. When the electrode was greater than three quarters of an inch above the nodal area, control ceased completely and could not be effected even by raising the voltage used. A similar distance was found to be the outer limit on passing the electrode below the sino-auricular node.

The two-point electrode gave the best control, using the internal application via the external jugular vein and superior vena cava. No complications were observed from this method.

A very transient auricular fibrillation was observed when the lower portion of the atria were being explored by the external stimulating electrode during the early studies. The fibrillation in both cases ceased immediately upon removing the electrode and applying it properly to the sino-auricular nodal region.

When the intravenous pacemaker electrode was in place in the superior vena cava it could be determined easily whether the electrical circuit was functioning. The elec-

trode was merely moved slightly laterally and contractions of the right dome of diaphragm, synchronous with the stimulating rate, could be observed.

Voltage of the stimulating current was difficult to assess because of the extreme brevity of the pulse duration (.002 sec.). The stimulus used was either a monophasic or biphasic pulse of sharp rise and exponential decay, with pulse duration varying between .02 and 2 milleseconds. The effective voltages, calculated to be 0.15 of peak voltages, ranged between 0.3 and 20.0 volts.

DISCUSSION

From the above experimental results it appears that heart action can be controlled satisfactorily by an electrical artificial pacemaker.

Cardiac arrest which occurs at low body temperature has proved suitable for study of the artificial pacemaker, and control of cardiac function has been effected. It is interesting to observe a complete survival in a dog whose heart action had been artificially maintained for as long as 30 minutes at low temperature, with no apparent ill effects. In the cold state the heart rate is greatly reduced and the most satisfactory artificial action was obtained by setting the dial of the stimulating device at a rate usual for that temperature. The heart rate could not be increased more than a few beats per minutes above this range, probably due to the increased activity phase described by Hegnauer, *et al.*,¹⁷ in dogs at low body temperature.

To apply this study to general hypothermia it is felt that it is possible to control heart action following serious cardiac arrest until the animal can be re-warmed to higher temperatures where spontaneous control can again take over. We have proposed the use of general hypothermia as a means of reducing the oxygen requirements of the body sufficiently to allow exclusion of the heart from the circulation and thus permit

FIG. 9.—Smoked drum tracing of application of the artificial pacemaker to a normally beating heart at a rate slower than its spontaneous rate. Note increase in pulse pressure due to increase in time for filling at the slower rate.

FIG. 10.—A smoked drum record of the effect on the heart rate and blood pressure of applying the artificial pacemaker, set at 180 a minute, to a heart spontaneously beating poorly at 90 a minute. Note the immediate rise in the heart rate and blood pressure, as well as the general improvement as a result of the procedure, shown at the right end of the record .

FIG. 11.—Another animal. The artificial pacemaker applied to a normally beating heart. Blood pressure is maintained when the rate is doubled.

FIG. 12.—A smoked drum record of the effect on blood pressure of right vagus nerve stimulation when heart is under control of artificial pacemaker. Note absence of fall in blood pressure until the artificial pacemaker is shut off while vagus stimulation persists.

intracardiac surgery under direct vision.^{1, 23} The use of an artificial pacemaker will allow resuscitation should cardiac arrest occur during the procedure. An intravenous electrode, as described, allows closure of the thoracotomy wound and permits resuscitative measures while the heart beats under artificial control, until spontaneous heart action takes over at the higher temperatures.

This study has been developed also with a view to resuscitation of animals¹⁸ under conditions similar to those encountered by human beings suffering from exposure to extreme cold.

The period of cardiac arrest that occurred in dogs at normal body temperature due to stimulation of the right vagus nerve has been of sufficient duration to demonstrate artificial heart action. It has been shown that these artificial beats are strong enough to maintain normal blood pressure.

Experimental vagus inhibition probably comes closest to duplicating the cardiac arrest that occurs in the operating room. The electrical impulse from the artificial pacemaker probably does nothing more than initiate normal sino-auricular node activity at controlled rates at a time when it is not normally functioning. Reid¹⁹ states that the prime requisite to produce activity of the sino-auricular node is for it to become electrically negative.

The actual pacemaker site is separated by thin tissue from the blood stream entering the heart through the superior vena cava. In this investigation the best results have been obtained with the stimulating pacemaker electrode in the superior vena cava against the deep surface of the sino-auricular node. One cannot overlook the ease of intravenous application compared to the thoracotomy approach. From the practical aspect, it is important to observe that intimate contact with the sino-auricular node is not essential for good control, since distances up to three quarters of an inch away from the nodal area were adequate.

The proximity of the phrenic nerve provides a simple test of circuit function without necessitating removal of the electrode. The apparent lack of serious complications makes the procedure safe experimentally.

When applied to a normally beating heart at normal or slower rates than usual, the artificial pacemaker quite easily takes over heart action and a slower or more rapid rate may be produced. In these experiments upon the beating heart the blood pressure has been raised or maintained. This is worth further study as a means of improving temporarily inefficient heart action.

With growing interest by many workers in intracardiac procedures,²⁰⁻²² the problems of arrhythmias, ventricular fibrillation and cardiac arrest become more prominent, and with them a greater need for the investigation of methods of control of heart beat.

SUMMARY

1. A technic for applying an artificial pacemaker to the hearts of dogs and rabbits has been described.

2. Two methods of application, one externally and the other internally via an electrode in the superior vena cava, have been used successfully.

3. Control of heart action by an electrical artificial pacemaker has been possible in 11 dogs cooled to low body temperature during standstill or extreme slowing of the heart.

4. At normal body temperature, brief arrest of the heart has been produced in 13 dogs and nine rabbits by right vagal stimulation. During this period of standstill, beats of good expulsive force have been produced.

5. It has been possible in hearts beating at normal or at reduced rates, to take over control of heart action by impulses from an electrical artificial pacemaker and to increase or decrease the heart rate at will.

6. The application of the artificial pacemaker has proved a relatively safe pro-

cedure. The possible clinical applications have been suggested.

CONCLUSIONS

It is possible to create good expulsive beats of the heart by applying electrical impulses to the region of the sino-auricular node during cardiac arrest, both at low and at normal body temperature.

It is also possible to take over control from the normal pacemaker in a heart beating spontaneously at a normal rate and to maintain thereafter a new rate either faster or slower than the original normal.

This is a safe procedure in animals and allows complete control of heart action and successfully maintains blood pressure.

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