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Berkovits

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[54] **SYNCHRONIZED ATRIAL AND VENTRICULAR PACER AND TIMING CIRCUITRY THEREFOR**

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[51] **Int. Cl.** **A61m 1/36**

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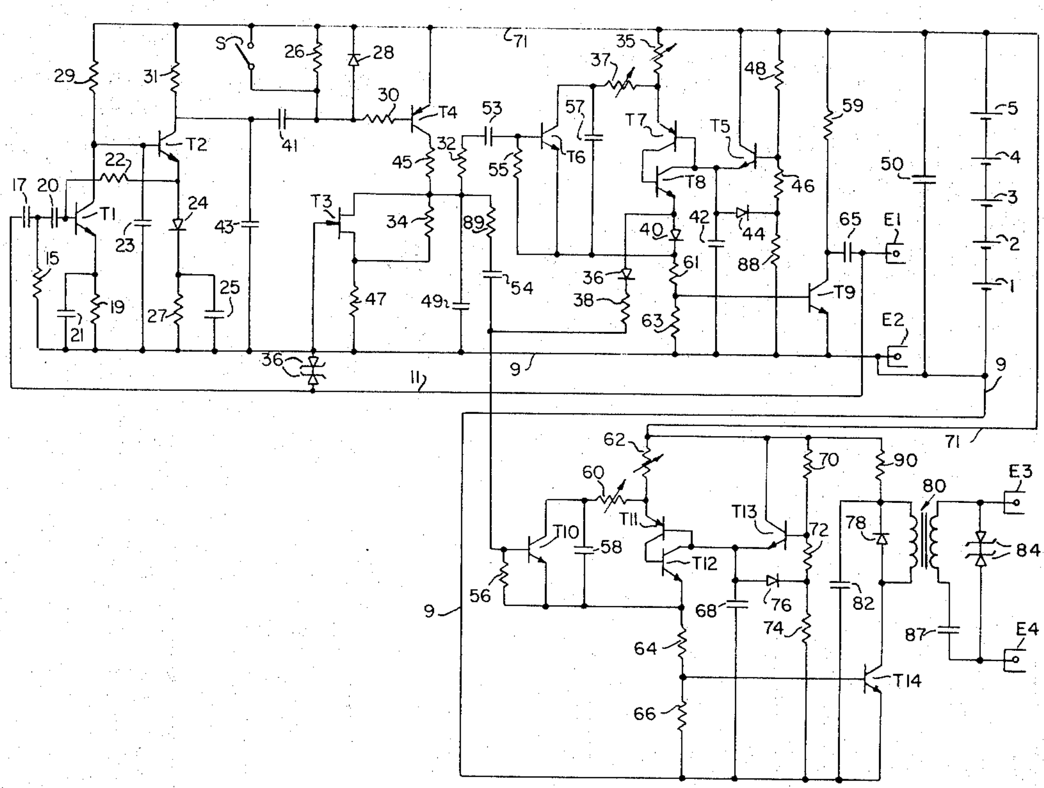
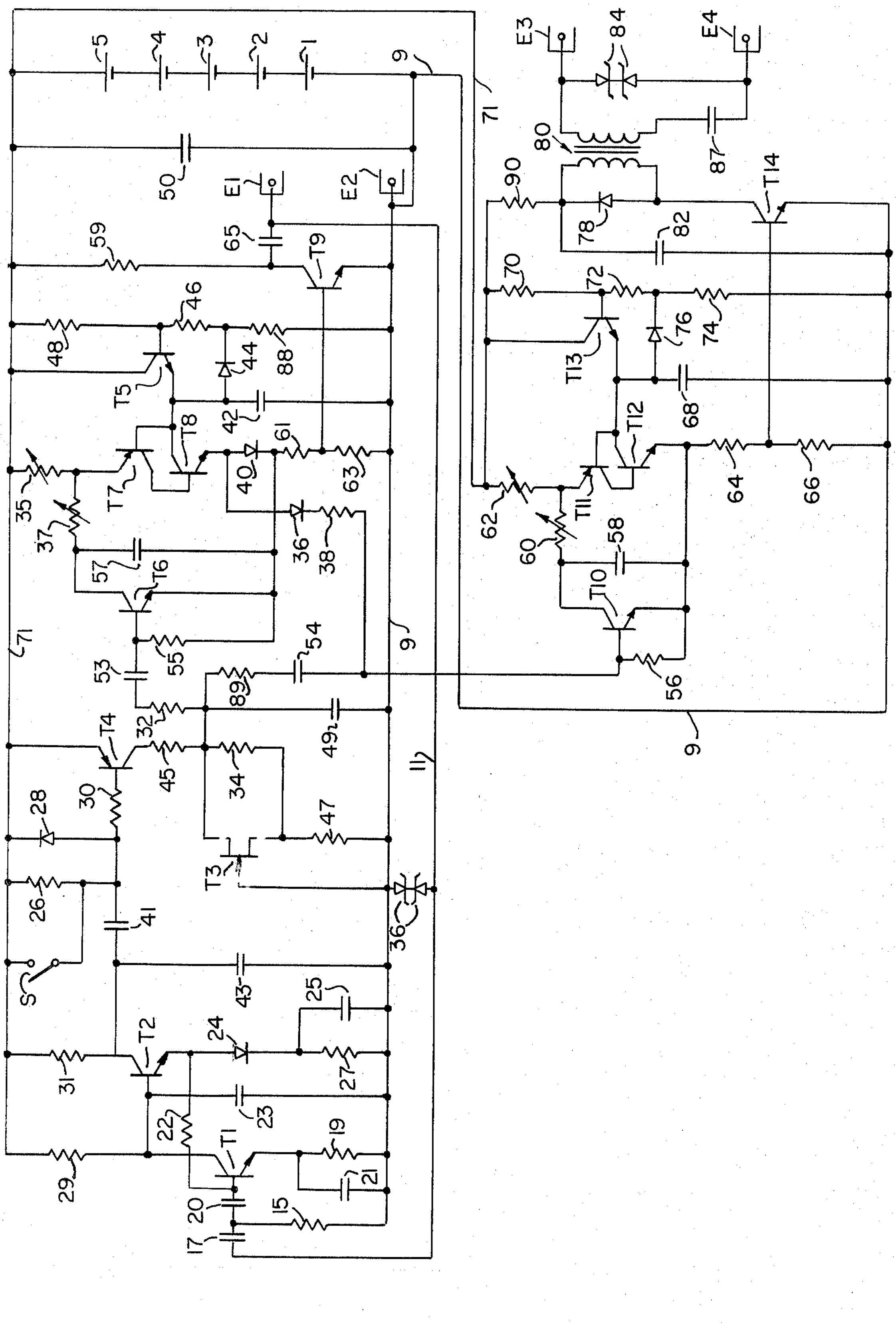
[57] **ABSTRACT**

There is disclosed an atrial and ventricular pacer which features a unique pacer timing circuit dependent upon voltage supply level only under certain conditions, and in which the atrial and ventricular pulsing circuits are synchronized to each other even if the ventricular beat detector fails or ventricular beat signals are masked by noise. In prior art pacers of this type, in the event the pacer operates in the continuous mode both pulsing circuits operate independently of each other. But in the present pacer the generation of a ventricular stimulating pulse re-starts the atrial timing period.

11 Claims, 1 Drawing Figure

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SYNCHRONIZED ATRIAL AND VENTRICULAR PACER AND TIMING CIRCUITRY THEREFOR

This invention relates to atrial and ventricular pacers, and more particularly to such pacers in which the atrial and ventricular pulse timing sequences are synchronized to each other.

In a typical ventricular demand pacer, a pulsing circuit is primed to generate an impulse at a predetermined time after the last natural heartbeat. If another natural heartbeat occurs during the timing interval of the pacer, an impulse is not generated and the timing period starts all over again. On the other hand, if a natural heartbeat does not take place by the end of the timing period a stimulating impulse is generated. For the proper operation of a demand pacer, the pacer circuitry must determine if a natural heartbeat has occurred. The largest magnitude electrical signal generated by the heart activity is that corresponding to ventricular contraction. To determine whether a natural heartbeat has occurred, a pair of electrodes is generally coupled to a ventricle. Since in most cases ventricular stimulation is required, the same electrodes can be used for both stimulating the ventricles and detecting a natural heartbeat.

In the presence of noise, erroneous operation of a demand pacer of this type can take place. The noise may result in the generation of an electrical signal on the ventricular electrodes, and the pacer circuitry may treat this noise as indicative of a natural heartbeat and inhibit the generation of a stimulating impulse even if one is required. In my U.S. Pat. No. 3,528,428 issued on Sept. 15, 1970, an improved demand pacer is disclosed. In this improved demand pacer, in the presence of noise the pacer timing period is not interrupted. Continuous stimulating impulses are generated, even if they are not required. It is better to provide an impulse even if it is not required than it is not to provide an impulse if it is required.

There are many patients with symptomatic atrial bradycardia even though they have normal AV conduction. In such a patient, the slow atrial rate causes the ventricular rate to slow down. Ventricular pacer stimulation has been used in the past to treat this disorder. For such patients, however, it would be better to provide atrial stimulation to thus control both the atrial and ventricular rates, with the additional benefit of the natural atrio-ventricular sequence. But such atrial stimulation would leave the patient unprotected from unpredictable AV block. Thus, provision should also be made for ventricular stimulation if it becomes necessary.

In my copending application Ser. No. 884,825 filed on Dec. 15, 1969 and issued as U.S. Pat. No. 3,661,158, there is disclosed an atrial and ventricular pacer. The first function of the pacer is to generate an atrial stimulating impulse. After a predetermined time interval, the pacer functions to generate a ventricular stimulating impulse. Four electrodes are provided — two for atrial stimulation and two for ventricular stimulation. The ventricular electrodes also serve to detect the occurrence of a ventricular contraction.

The pacer exhibits two timing or escape intervals. The ventricular escape interval is 160–250 milliseconds longer than the atrial escape interval. The ventricular escape interval is greater than the normal interval between two heartbeats (as in a typical demand pacer).

The atrial escape interval is shorter than this ventricular escape interval by a pre-set interval. Both timing periods begin with the generation of the last heartbeat (natural or stimulated). If another ventricular contraction does not occur within the atrial timing period, that is, in the absence of a premature ventricular contraction, the atrial stimulating impulse is generated. The atria contract and fill the ventricles with blood. In the event the ventricles contract (i.e., there is no AV block), the detected signal on the ventricular electrodes resets both timing circuits and the ventricular impulse is not generated. In the event the ventricular contraction does not occur, a ventricular impulse is generated at the end of the ventricular timing interval.

Both pulse generating circuits are keyed to the detection of a ventricular beat. The detection of such a beat resets both timing circuits; an atrial stimulating pulse is generated after a predetermined time interval has elapsed following the last ventricular beat (spontaneous or stimulated), and a ventricular stimulating pulse — if one is needed — is generated after another (longer) predetermined time (ventricular escape) interval has elapsed following the last ventricular beat. The pacer includes circuitry for causing it to operate in the continuous mode in the presence of noise. For example, if the ventricular beat detecting circuit operates at a fast rate as a result of interference from 60-Hz stray signals, the pacer functions in the continuous mode. Atrial and ventricular stimulating pulses are generated at fixed rates independent of the operation of the ventricular beat detector. Similarly, if the ventricular beat detector fails, atrial and ventricular stimulating pulses are generated at fixed rates and the pacer operates in the continuous mode for the remainder of its life or until the malfunction in the ventricular beat detector corrects itself. However, because the timings of the two pulse generators are keyed to the detection of ventricular beats, when such beats are no longer detected, or are no longer recognizable, synchronism between the two pulsing circuits is lost. In fact, since it is almost impossible for the timing periods of both pulsing circuits to be identical, the atrial and ventricular stimulating pulses are generated at different rates.

It is a general object of the present invention to provide an improved atrial and ventricular pacer. It is a further object of the present invention to provide an atrial and ventricular pacer wherein pulsing circuits operate in synchronism even if the ventricular beat detector is disabled because of effects of noise, or if the detector malfunctions. It is another object of the present invention to provide a unique pacer timing circuit dependent upon voltage supply level only under certain conditions.

In the case of a demand pacer which does not provide atrial stimulation, such as that disclosed in my U.S. Pat. No. 3,528,428, when the pacer operates in the continuous mode each generation of a ventricular stimulating pulse triggers a new ventricular timing period. Similarly, if a spontaneous ventricular beat is detected, the ventricular timing period is re-started. In prior art atrial and ventricular pacers, the ventricular timing period re-starts whenever a spontaneous ventricular beat is detected or whenever a ventricular stimulating pulse is generated. However, the atrial timing period is re-started only when a ventricular beat (spontaneous or stimulated) is detected. In accordance with the principles of the present invention, however, the generation of a ventricular stimulating pulse also re-starts the atrial timing period.

Thus, if spontaneous ventricular beats are detected, the detecting circuit re-starts both timing periods. But if spontaneous ventricular beats are not detected and the pacer therefore operates in the continuous made, each generation of a ventricular stimulating pulse re-starts the atrial timing period along with the ventricular timing period. The two pulsing circuits are maintained in synchronism in all cases.

It is a feature of my invention to provide in an atrial and ventricular demand pacer a mechanism for re-starting the atrial timing period whenever a ventricular stimulating pulse is generated independent of the detection of a ventricular beat.

Further objects, features and advantages of my invention will become apparent upon consideration of the following detailed description in conjunction with the drawing which depicts the illustrative embodiment of the invention.

In the pacer shown in the drawing, electrodes E1 and E2 are the ventricular stimulating electrodes, and electrodes E3 and E4 are the atrial stimulating electrodes. The ventricular timing and stimulating circuit is contained in the drawing between capacitor **53** and electrodes E1 and E2. Capacitor **65** is initially charged by current flowing from batteries **1–5** through resistor **59**, electrodes E1 and E2, and the patient's heart in a time much shorter than the interval between successive heartbeats. The magnitude of resistor **59** is low enough to permit rapid charging of capacitor **65** but high enough to prevent significant attenuation of the signal detected across electrodes E1 and E2, these terminals being connected to the ventricular beat detecting circuit over conductors **9** and **11**. When transistor T9 is triggered to conduction, the capacitor discharges through it, current flowing from the capacitor through the collector-emitter circuit of the transistor, electrode E2, the heart itself, and electrode E1. The discharge of capacitor **65** through the electrodes constitutes the impulse to stimulate the ventricles if necessary. As soon as transistor T9 turns off, capacitor **65** charges once again in preparation for the next cycle. The capacitor serves simply as a source of current when an impulse is necessary. Capacitor **65** is not involved with the various timing sequences used to control the selective generation of impulses.

The capacitor always charges to the peak battery voltage. Because it discharges through an essentially short-circuited transistor switch, the magnitudes of the impulses do not vary as the battery impedance increases with aging. Nor is there any waste of energy between manufacture and implantation — although transistor T9 is gated on during each cycle, as long as the electrodes are open-circuited capacitor **65** cannot discharge.

The capacitor charges, as well as discharges, through the heart so that the net DC current through the electrodes from the pacer is zero. Otherwise, electrolytic processes in the heart cells could dissolve the electrodes.

Transistors T7 and T8, connected as shown, are the equivalent of a conventional silicon controlled rectifier. Both are normally non-conducting. When the emitter electrode of transistor T7 goes sufficiently positive, the transistors conduct and current flows through the emitter circuit of transistor T8. Current continues to flow until the potential at the emitter of transistor T7 drops below a predetermined value.

Transistor T9 is a simple current amplifier which is normally non-conducting. When transistor T8 conducts, however, the emitter current flowing through diode **40** and resistors **61** and **63** causes the potential at the base of transistor T9 to increase. At such a time transistor T9 is biased to conduction and capacitor **65** can discharge through it as described above.

The apparatus can be used in a free-running mode, that is, an impulse can be generated at a 72-pulse-per-minute rate, for example, independent of the occurrence of natural heartbeats. In such a case, switch S is closed and, as will be described below, transistor T6 is never pulsed on. Initially, capacitor **57** is discharged and transistors T7 and T8 are non-conducting. Current flows from batteries **1–5** through resistors **35** and **37**, capacitor **57**, and resistors **61** and **63**. The current through resistors **61** and **63** is insufficient to turn on transistor T9. As the capacitor charges, the junction of the capacitor and resistor **37** increases in potential. Thus the emitter of transistor T7 increases in potential. Eventually the potential is sufficient to trigger the relaxation oscillator consisting of transistors T7 and T8. Capacitor **57** discharges through resistor **37** and these two transistors. At the same time current flows through the collector-emitter circuit of transistor T8, and resistors **61** and **63**. Transistor T9 conducts and capacitor **65** discharges through it to provide an impulse to the ventricles. As soon as capacitor **57** has discharged sufficiently and the potential of the emitter of transistor T7 has dropped to a low enough value, all of transistors T7, T8 and T9 turn off and the impulse is terminated. Capacitor **65** immediately recharges, and capacitor **57** starts charging once again in preparation for the next impulse.

The charging period of capcitor **57**, that is, the interval between impulses, is determined by the magnitude of the capacitor, and the magnitudes of resistors **35, 37, 61** and **63**. Resistors **37, 61** and **63** are very small in comparison to the magnitude of resistor **35**. Consequently, it is the magnitude of resistor **35** which determines the inter-pulse interval. As the magnitude of resistor **35** is adjusted the rate of the impulses varies.

Similarly, it may be desirable to adjust the width of each impulse delivered to the heart. Capacitor **57** discharges through resistor **37** and transistors T7 and T8. The width of the impulse delivered by capacitor **65** is determined by the discharge time of capacitor **57**, that is, the time period during which transistors T7 and T8 conduct and thereby turn on transistor T9. By varying the magnitude of resistor **37** the width of each impulse can be adjusted. In the case of an implantable pacer, the magnitudes of resistors **35** and **37** would be adjusted prior to implanting the apparatus in the patient.

When switch S is opened, i.e., in the case of a pacemaker required to operate in the demand mode, the same type of free-running operation would take place were there no input to the base of transistor T6 through capacitor **53**. Transistor T6 would remain non-conducting and would not affect the charging of capacitor **57**. However, with switch S open, a pulse is transmitted through capacitor **53** to the junction of biasing resistor **55** and the base of transistor T6 to cause the transistor to conduct whenever a ventricular beat is detected. Capacitor **57** discharges through the collector-emitter circuit of the transistor. In such a case, the timing cycle is interrupted and the junction of capacitor **57** and resistor **37** does not increase in potential to the point where transistors T7 and T8 are triggered to conduction. After capacitor **57** has discharged through transistor T6, the transistor turns off. The capacitor then starts charging once again. The new cycle begins immediately after the occurrence of the last ventricular contraction so that the next impulse, if needed, will be generated immediately after the next natural heartbeat should have been detected were the heart functioning properly.

A similar circuit is provided for generating an atrial stimulating pulse. Electrodes E3 and E4 are implanted in the patient's heart to stimulate his atria. Capacitor **58** charges through potentiometers **60** and **62**. After a predetermined interval, when the capacitor voltage has reached the level required to control conduction of transistors T11 and T12, the two transistors conduct and forward bias the base-emitter junction of transistor T14, which in turn controls the generation of an atrial stimulating pulse on electrodes E3 and E4. The width of each pulse is determined by the setting of potentiometer **60** which determines the time required for capacitor **58** to discharge through transistors T11 and T12. The inter-pulse interval is determined by the setting of potentiometer **62** which determines the time required for capacitor **58** to charge to the level which causes transistors T11 and T12 to conduct.

Any pulse delivered to the junction of biasing resistor **56** and the base of transistor T10 through capacitor **54** as a result of the detection of a ventricular beat causes transistor T10 to conduct along with transistor T6. At the same time that capacitor **57** discharges through transistor T6, capacitor **58** discharges through transistor T10. In such an event, the timing period of the atrial pulsing circuit is not concluded and an atrial stimulating pulse is not generated. Instead, the timing begins once again.

A capacitor comparable to capacitor **65** is not provided to store charge preparatory to the generation of each atrial stimulating pulse. Instead, the conduction of transistor T14 causes a pulse to be transmitted through transformer **80** to electrodes E3 and E4. When the transistor turns on, current flows through the primary winding of transformer **80** and the collector-emitter circuit of transistor T14. The current pulse through the primary winding of transformer **80** causes a voltage pulse to appear across the secondary winding of the transformer. This pulse is transmitted through capacitor **87**. Electrode E3 goes positive with respect to electrode E4 and current flows through the atrium to which the electrodes are connected.

Capacitor **87** is provided to prevent the flow of direct current in the event the electrodes become polarized. Zener diodes **84** are provided to safeguard against an excessive signal appearing across the electrodes resulting from an external source; the diodes conduct (one in the forward direction and one in the reverse direction) if the signal exceeds a few volts. In such a case, the magnitude of the pulse extended in the reverse direction through transformer **80** to the collector circuit of transistor T14 can cause no damage.

Diode **78** is provided to allow the current through the primary winding of the transformer to dissipate when transistor T14 turns off at the end of each pulse. The current continues to flow in the same direction through the primary winding but it now flows through diode **78**

instead of transistor T14. The diode is reverse biased when transistor T14 conducts so that during the generation of the current pulse it has no effect on the circuit operation. The use of the diode in this manner allows the rapid disappearance of the magnetic field produced by the current flow through the primary winding at the end of the atrial stimulating pulse.

Potentiometer **62** has a value such that capacitor **58** charges to the level required for the conduction of transistors T11 and T12 after 600 milliseconds have elapsed since the last capacitor discharge. An atrial stimulating is thus generated 600 milliseconds after a ventricular beat. It should be noted that the atria are stimulated following an atrial contraction during a normal heartbeat. Actually, if the atria have contracted an atrial stimulating impulse on electrodes E3 and E4 is not required. However, if such an impulse is generated following the atrial contraction, that is, during the refractory interval of the atria, it has no effect on the beating action of the patient's heart. (The generation of an atrial stimulating impulse prior to the natural atrial contraction can induce an atrial premature beat which is not desirable.)

Potentiometer **35** in FIG. **1** has a value such that the timing interval for the ventricular stimulation is 800 milliseconds. Thus, a ventricular stimulating pulse occurs 800 milliseconds after a previous ventricular beat which is slightly longer than the "normal" inter-beat interval. If a spontaneous ventricular beat is detected, both timing cicuits are reset and a pulse is not generated on electrodes E1 and E2. This is the desired demand-type operation. If a natural heartbeat does not occur within **800** milliseconds after the last heartbeat, an impulse is generated on electrodes E1 and E2 to stimulate the ventricular contraction. It should be noted that if the heart beats naturally, there will be no ventricular stimulation by the pacemaker. However, there will be atrial stimulation because the 600-millisecond atrial timing interval is less than the natural inter-pulse interval. But in the event a natural atrial contraction does not take place, the atrial stimulation is required in order that the heart function more efficiently. The ventricular stimulation, of course, is provided to correct any AV block. A normal ventricular contraction can occur approximately 120–160 milliseconds after the atrial stimulation. The ventricular timing period is 200 milliseconds longer than the atrial timing period; sufficient time is allowed for a natural ventricular contraction before a ventricular stimulating impulse is generated. In general, the ventricular timing period should exceed the atrial timing period by 160–250 milliseconds.

It should be noted that the operation of the atrial timing circuit is keyed to the detection of a ventricular contraction on electrodes E1 and E2. It is highly desirable to key the atrial timing circuit to the beating of the patient's heart — were a free-running generator provided to stimulate the atria, the timing of the beating of the patient's heart might be seriously affected. While the natural timing might change, the circuitry timing would be invariant. For this reason, capacitor **58** is discharged following any beating of the patient's heart. It is the detection of a ventricular beat which serves to reset both timing periods. Of course, this results in the continuous generation of impulses at electrodes E3 and E4 if the heart is beating normally (even though impulses at electrodes E1 and E2 are not generated) because each ventricular beat is detected after the impulse on electrodes E3 and E4 has been generated. However, the generation of an atrial stimulating impulse during the refractory interval of the atria has been found not to interfere with the normal beating of a patient's heart. (The same is not true of the generation of a ventricular stimulating impulse following a ventricular contraction, and this is a reason for the use of the demand-type pacer in the first place.)

Referring to the ventricular timing and pulsing circuit, it is the potential at the base of transistor T7 (collector of transistor T8) which determines the reference level which when exceeded by the voltage on capacitor **57** results in the conduction of the transistors and the generation of a ventricular stimulating pulse. One problem with pacers in general is that the potentials of the batteries decrease with age. The pacer timing is determined by how long it is necessary for capacitor **57** to charge until it reaches the reference level. It is apparent that if the reference level and the charging voltage both change with age, the pacing rate may vary. The pacer of the invention includes a unique circuit for insuring a constant pacing rate independent of battery voltage.

Capacitor **57** charges from a potential determined by the magnitudes of the five sources **1–5**. The reference potential at the base of transistor T7, as will be described, is similarly a function of the total battery potential. However, the reference potential is derived in a manner such that the ratio of the charging voltage to the firing level is constant independent of the total supply voltage. Consequently, since the voltage across capacitor **57** rises exponentially, it always takes the same time interval for the capacitor voltage to reach the reference level, no matter how the total battery supply voltage varies.

Assume that the total potential of sources **1–5** is equal to V**1**. Resistors **48, 46** and **88** comprise a voltage divider, and the potential at the base of transistor T5 can be considered to be V**2**. Assuming a 0.1-volt drop across the base-emitter junction of transistor T**5**, the potential at the base of transistor T7 is equal to V2 – 0.1 volts. Further assuming that it requires a 0.1-volt drop across the emitter-base junction of transistor T7 for the transistor to conduct, it is apparent that transistors T7 and T8 will turn on when the emitter potential of transistor T7 (approximately equal to the potential at the junction of potentiometer 37 and capacitor **57**) is equal to V**2**. Since the ratio of potentials V2 and V1 is constant independent of the value of V1 since potential V2 is derived through a resistor divider, it is apparent that capacitor **57** charges exponentially to a predetermined percentage (V2/V1) of the charging voltage in a time which is independent of the magnitude of the charging voltage (V1) itself. Consequently, the pacing rate is independent of battery aging.

Capacitor **42** charges to a potential equal to V2– 0.1 volts. When transistors T7 and T8 conduct, the capacitor discharges slightly through transistor T8, but following termination of the ventricular stimulating pulse the capacitor quickly re-charges through transistor T5. The function of diode **44**, across which there is a 0.1-volt drop, is to prevent capacitor **42** from attempting to charge to a level higher than .1 volts above the potential at the junction of resistors **46** and **88**. resistors **48, 46** and **88** are selected such that the potential at the junction of resistors **46** and **88** is V2– 0.2 volts. In effect, transistor T5 functions as an emitter follower to maintain a voltage across capacitor **42** (V2– 0.1 volts) such that the firing level of V2 volts is always a fixed percentage of the charging potential V1 independent of the magnitude of V1.

A similar reference potential deriving circuit including resistors **70, 72,** and **74,** transistor T13, diode **76** and capacitor **68** is provided for the atrial timing and pulsing circuit.

The ventricular timing and pulsing circuit includes a diode **40** in the emitter circuit of transistor T8. When the pacer operates in the continuous mode, that is, when switch S is closed (the closing of the switch can be controlled externally, e.g., by using a magnet as is known in the art), capacitor **57** does not discharge through transistor T6. The capacitor only discharges through transistors T7 and T8. The discharge pulse continues until transistors T7 and T8 are no longer forward biased. By providing diode **40,** the transistors turn off when the capacitor voltage drops to a value which is higher than the turn-off voltage which would otherwise be the case in the absence of the diode since there is a relatively fixed drop across the diode when it conducts. In the demand mode, however, when transistor T6 discharges capacitor **57,** the discharge is greater. Consequently, it requires a longer time for capacitor **57** to charge to the firing level following the detection of a spontaneous ventricular beat than it does following the generation of a ventricular stimulating pulse. This effect is known as hysteresis — the continuous pacing rate is faster than the demand rate.

When the pacer is operated in the demand mode, capacitor **57** discharges almost completely through transistor T6. Since the capacitor starts to charge from an initially discharged condition, the pacing rate is determined almost solely by the charging potential V1 and the reference potential V2 whose ratio is fixed. However, when the pacer is operated in the continuous mode, capacitor **57** starts to charge from an initially higher level since diode **40** prevents a complete discharge of the capacitor. Consequently, when the pacer is operated in the continuous mode the pacer rate is a function of the charging potential V1 since the effective charging potential is equal to V1 minus the initial voltage across capacitor **57.** The physician is thus enabled to determine the condition of the battery simply by closing switch S so that the pacer operates in the continuous mode; by measuring the pacer rate, it is possible to determine the extent to which the battery voltage has decreased. Thus the circuit arrangement not only provides a demand rate which is essentially independent of battery voltage, but also allows the battery condition to be determined by switching the pacer to the continuous mode and examining an ECG waveform on an oscilloscope.

The function of capacitor **50,** which is connected across the series string of batteries, is to reduce the source inpedence of the batteries; capacitor **50** shorts AC signals through it so that they are unaffected by any source impedance. Capacitor **82** in the atrial pulsing circuit is provided for another purpose. It is desirable to isolate the atrial electrodes E3 and E4 from the ventricular beat detecting circuit which is coupled to electrodes E1 and E2 over conductors **9** and **11.** It is for this reason that transformer **80** is used in the first place. To decouple the two circuits as much as possible, capacitor **82** is provided. Current flows from batteries **1–5** through resistor **90** to charge the capacitor. It is the voltage across capacitor **82** that functions as the supply for transistor T**14**. Thus when an atrial stimulating pulse is generated and current flows through transistor T14, the pulse is shorted through capacitor **82** and is not coupled back to the five batteries. Were the pulse coupled back to the batteries, a voltage spike might appear across conductors **9** and **11** and the ventricular beat detector could erroneously operate as though a ventricular beat were detected when instead an atrial stimulating pulse is generated.

It is the function of the circuitry to the left of the drawing to detect a natural heartbeat (ventricular contraction), to the exclusion of other undesired signals, and, in response thereto, to apply a positive pulse to the base of transistor T6 and to the base of transistor T10 for the purpose of interrupting the charging cycles of capacitors **57** and **58.**

The natural beating action of the heart produces electrical signals which are characteristic of successive steps in the occurrence of each heartbeat. A heart beating in normal or sinus rhythm produces electrical signals conventionally identified as P, Q, R, S and T waves.

It is generally recognized by those skilled in the art that it is preferable to distinguish the QRS complex in an electrocardiogram from the P and T waves for the purpose of detecting a natural heartbeat. Actually, with respect to implantable pacers it is the cellular electrogram in the vicinity of the electrodes which is important, not the skin electrocardiogram, since the pacer responds to the electrical signals generated by the cells in the vicinity of the electrodes. The cellular electrogram is generally considerably different from the skin electrocardiogram. The latter is the integral of all the cellular electrograms generated by a beating action of the heart. Because the various cells generate their signals at different times during each heartbeat, the integral (electrocardiogram) is in many respects dissimilar from an individual cellular electrogram. However, just as the electrocardiogram exhibits a sharply rising R pulse so does the cellular electrogram. It is the sharply rising pulse of the electrogram which is the best indication of a natural heartbeat. Although references below are made to the QRS complex of an electrocardiogram it must be borne in mind that with respect to the electrodes implanted in the patient's heart it is the sharply rising pulse of the cellular electrogram which is of importance. It has become the practice in the art to focus on the QRS complex of the electrocardiogram, rather than the individual cellular electrogram, primarily because the R wave in the electrocardiogram does for the most part correspond to the sharply rising pulse of the cellular electrogram.

Using the techniques of frequency analysis, it can be shown that the R peak comprises frequency components primarily in the 20–30 Hz region. The P and T waves comprise for the most part lower frequency components. To avoid triggering of transistors **T6** and **T10** by P and T waves, various filters are provided in the circuit to filter out frequencies below 20 Hz. Of course, it is advantageous to provide additional filters to filter out frequencies above 30 Hz, and particularly 60-Hz frequency signals. Such filters are incorporated in the pacer depicted in the drawing although it has been found that such filters are not totally effective in preventing the triggering of transistors T6 and T**10** by 60-Hz stray signals. For this reason, while various filters are associated with amplifying stages T1 and T2, a rate discrimination circuit (including transistors T3 and T4, resistors **34, 45** and **47**, and capacitor **49**) is provided to prevent triggering of transistors T6 and T10 by **60**-Hz stray signals. This rate discrimination circuit will be described below after the frequency discrimination circuit is first considered.

Transistor T1 is normally conducting, the emitter terminal of the transistor being connected through resistor **19** and conductor **9** to the negative terminal of battery **1**, and the base of the transistor being connected through resistor **22** to a more positive pontential at the emitter of transistor T**2**. The electrical signals picked up by the electrodes implanted in the patient's heart are coupled across capacitor **17** and resistor **15** in the base circuit of transistor T1. Signals of either polarity are amplified by transistor T**1**. The transistor is biased for class A operation because the polarity of the detected signal may be of either type depending on the manner in which the electrodes are implanted.

Zener diodes **36** bridge electrodes E1 and E**2**. It is possible that very high voltages can appear across the electrodes. For example, if defibrillation equipment is used, a very high voltage may be applied to the patient's heart. To avoid damage to the pacer circuitry, the large voltage signals are short-circuited through the Zener diodes. The function of the diodes is similar to that of Zener diodes **84.**

Capacitors **17** and **20** and resistor **15** emphasize the step function in the cellular electrogram. These elements comprise a differentiator which emphasizes the frequency components above approximately 20 Hz. For such signals, the voltage drop across resistor **15** is appreciable and the input to transistor T**1** is relatively large. For lower frequency signals, however, the voltage drop across capacitor **17** is much greater, and a smaller input signal is applied across the base-emitter junction of transistor T**1.**

Resistor **19** and capacitor **21** in the emitter circuit of transistor T1 serve a similar function. The impedance of the parallel circuit increases as the frequency decreases. The emitter impedance provides negative feedback for the transistor, and the overall gain of the transistor decreases as the frequency decreases.

The amplified signal at the collector of transistor T1 is applied across the base-emitter junction of transistor T2, this transistor also being biased for class A operation. Transistor T2 further amplifies the detected signals. Capacitor **25** and resistor **27** in the emitter circuit of transistor T2 serve the same function as resistor **19** and capacitor **21** in the emitter circuit of transistor T**1.** This third differentiator further limits the low frequency response of the detecting circuit to discriminate against the P and T waves and any other frequences well below 20 Hz.

Resistor **29** and capacitor **23** serve as an integrator to reduce high frequency noise components well above 30 Hz. The higher the frequency, the lower the impedance of capacitor **23,** the smaller the overall collector impedance of transistor T1, and the lower the gain of the stage. Resistor **31** and capacitor **43** in the collector circuit of transistor T2 serve the same function. Actually, these four elements serve to attenuate frequencies well above 60 Hz and have little effect on 60 Hz signals. In the illustrative embodiment of the invention the rate discrimination stage distinguishes 60-Hz stray signal from desired signals.

Transistor T2 functions primarily as an amplifying stage. However, it also serves to provide a biasing potential for transistor T1. In typical prior art pacers, a tap on batteries 1–5 is used to bias the base of transistor T1 to class A operation. It is known in the art, however, that the greater the number of battery taps, the greater the unreliability of the pacer because the failure of just one battery may cause the entire pacer to fail. In the preferred embodiment of the invention, there are no battery taps at all. However, in such a case it is necessary to derive an intermediate positive potential to bias the base of transistor T1 for class A operation. This is accomplished by connecting resistor **22** between the emitter of transistor T2 and the base of transistor T1. The positive potential at the emitter of transistor T2 (equal to the voltage drop across diode **24** and resistor **27**) is extended through resistor **22** to bias transistor T1 for class A operation. This DC feedback eliminates the need for a battery tap. Diode **24** serves simply as a level-shifting diode — it increases the potential at the emitter of transistor T2 by the drop across it without affecting the AC gain of the stage.

AC signals at the collector of transistor T2 are coupled through capacitor **41** and resistor **30** to the base of transistor T4. The overall gain characteristic of stages T1 and T2, from terminals E1 and E2 to the collector of transistor T2 and conductor **9**, is such that signals in the 20–30 Hz region are amplified to the greatest extent. The gain curve falls off very rapidly below 20 Hz such that the frequency components characteristic of the P and T waves are not amplified sufficiently for turning on transistor T4. For frequency components above 30 Hz, the gain for 60-Hz signals is only slightly less than the maximum gain. However, for signals considerably higher, e.g., above 150 Hz, the gain is low enough to prevent false operation of transistors T3 and T4.

If transistor T4 requires a signal of approximately 1 volt to conduct, and the maximum gain of stages T1 and T2 is above **50**, it is apparent that **20**-mv signals in the 20–30 Hz region at the electrodes can trigger transistor T4 to conduction. The 20–30 Hz components in the electrical signal generated by the beating of the heart in the vicinity of the electrodes is typically above 20 mv. The frequency components characteristic of the P and T waves are not only 2–3 times smaller in magnitude than those characteristic of the R wave, but since the gain of stages T1 and T2 in the region around 5 Hz is only a fraction of the maximum gain, these signals do not trigger transistor T4 to conduction.

A pulse transmitted through capacitor **41** and resistor **30** to the base of transistor T4 causes the transistor to conduct. It is necessary that the transistor conduct whenever a ventricular beat is detected, no matter what the polarity of the pulse transmitted through capacitor **41**. If the pulse is negative, diode **28** does not conduct; the circuit operation is not affected and the negative pulse at the base of transistor T4 causes the transistor to conduct. In the case of a positive pulse, the diode conducts rather than transistor T4. However, at the end of the pulse, the trailing edge constitutes a negative step and diode **28** is reverse biased. During the positive pulse, capacitor **41** charges through diode **28**. At the end of the pulse, capacitor **41** discharges through resistors **26** and **31**. While the capacitor is discharging, a negative potential is extended to the base of transistor T4 and the transistor conducts. Thus no matter what the polarity of the detected signal, transistor T4 turns on whenever a ventricular beat is detected. It is the turning on of transistor T4 which controls the discharge of capacitors **57** and **58**. it should be noted that with switch S closed, the pacer functions in the continuous mode because all pulses at the collector of transistor T2 are shorted through the switch and by-pass the base-emitter junction of transistor T4. Consequently, transistors T6 and T10 are not turned on to discharge respective capacitors **57** and **58**, and the two capacitors discharge through respective transistors T7 and T8, and T11 and T12.

Transistor T4 is normally non-conducting. However, when a negative signal is transmitted through capacitor **41** the transistor turns on and current flows from battery **5** through the emitter-collector circuit of the transistor, resistor **45**, and the parallel combination of capacitor **49** and resistors **34** and **47**. The capacitor thus charges toward a maximum voltage determined by batteries **1–5**, the drop across transistor T4, and resistors **45**, **34** and **47**. If the emitter-collector circuit of the transistor is considered to have negligible impedance, the charging current is determined by the magnitude of the batteries, the magnitudes of elements **34**, **45**, **47** and **49** and the effect of FET transistor T3. The magnitude of the negative input signal is of no moment. As long as it is above the threshold value necessary for controlling the conduction of transistor T4, a current pulse of sufficient magnitude will be delivered to charge fully capacitor **49**.

Each current pulse causes capacitor **49** to charge, current flowing through resistor **45** and the capacitor. (Some of the current flows through resistors **34** and **47** but capacitor **49** charges to the maximum potential determined by the source voltage, resistors **34**, **45** and **47**, and transistor T3.) When the pulse terminates, capacitor **49** starts discharging through resistors **34** and **47**, and transistor T3. Assuming that each charging pulse is sufficient to charge capacitor **49** to the fullest extent possible, when the pulse terminates capacitor **49** starts discharging from a maximum level. If the capacitor fully discharges by the time the next charging pulse is delivered, the capacitor will then recharge to the maximum voltage, after which it will fully discharge once again. The potential across capacitor **49** is AC-coupled through capacitor **53** to the base of transistor T6 and through capacitor **54** to the base of transistor T10. Each charging pulse increases the potential across capacitor **49** from zero to the maximum voltage. The positive step is sufficient to cause transistors T6 and T10 to conduct, thereby discharging capacitors **57** and **58** and inhibiting the next impulses which would otherwise have been generated.

Consider now charging pulses which occur at a faster rate, e.g., at a rate of 72 per minute which is expected as a result of natural heartbeats. Each charging pulse charges capacitor **59** to the maximum voltage. The capacitor then starts to discharge but before the discharge is complete another charging pulse occurs. The capacitor immediately charges to the maximum voltage and then starts to discharge once again. The capacitor never fully discharges, but the minimum voltage across it (that at the end of the discharge cycle when the next charging pulse is received) is low enough such that the increase in the capacitor voltage with the occurrence of each charging pulse is still sufficient to trigger transistors T6 and T10. Consequently, each charging pulse which results from a natural heartbeat resets both timing circuits.

Consider now the effect of 60-Hz signals on the circuit. If a stray 60-Hz signal is applied to the base of transistor T3, the transistor conducts 120 times per second. Consequently, charging pulses are delivered to capacitor **49** at the rate of 120 per second. This is a rate considerably greater than 72 per minute. Each pulse fully charges capacitor **49** and the next pulse is delivered before the capacitor has had an opportunity to discharge to any meaningful extent. Consequently, although each pulse fully charges the capacitor the increase in the capacitor voltage is negligible because the capacitor voltage never decreases much below the maximum potential. Consequently, steps of negligible magnitude are transmitted through capacitors **53** and **54** to the base of transistor **T6** and the base of transistor **T10**. Each transistor requires a signal of approximately 0.5 volts for conduction, and the step functions delivered through capacitors **53** and **54** are well below this value as the result of unipolar pulses from transistor **T4** which occur at a rate of 120 per second.

Activations of transistor T3 at a rate above 40 per second (an inter-activation period of 25 milliseconds) are sufficient to prevent appreciable discharge of capacitor **49** and the triggering of transistors **T6** and **T10**. It will be seen that should any 60-Hz signals, or signals of any higher frequency, be present in the circuit, step functions of insufficient magnitude to trigger transistors **T6** and **T10** are transmitted through capacitors **53** and **54**. Transistors **T6** and **T10** remain non-conducting and the pacer operates in its free-running mode. Even if there are natural heartbeats at this time, they have no effect. Each natural heartbeat causes a charging pulse to be delivered to capacitor **49**, but it has no effect since the capacitor is at all times charged to almost its peak value. Only in the absence of undesirable high frequencies does the capacitor have an opportunity to discharge prior to the delivery of a current pulse resulting from a natural heartbeat. It is only at this time that each natural heartbeat results in the conduction of transistors **T6** and **T10**, and the resetting of the timing circuits. In effect, capacitor **49** and the related elements can be thought of as a high inertia switch. This switch cannot respond to beats above a rate of 40 per second. Any repetitive signal above 40 per second is ineffective to de-activate the impulse generating circuits.

Of course, during the time that stray 60-Hz signals, or other undesirable signals, are present, the pacer operates in its free-running mode along with the natural beating of the patient's heart. This may be disadvantageous, but it is far better than allowing the pacer to cease functioning at all — a disastrous condition if at the particular time the patient's heart has stopped functioning.

Were transistor T3 omitted, the extent of the discharge of capacitor **49** would depend upon the supply voltage. This is because the capacitor would initially charge to a value proportional to the magnitude of the source, and then discharges exponentially. Since the percentage discharge of a capacitor in an RC circuit is a function of time only, not the initial voltage across the capacitor, the extent of the discharge would vary with the battery voltage; as the supply voltage would decrease with age, the capacitor would discharge to a lesser extent in any given interval of time. This, in turn, would decrease the cut-off rate of noise pulses which automatically convert the pacer to the continuous mode of operation. The provision of transistor T3 insures that capacitor **54** always discharges to the same extent in any given interval of time independent of the magnitude of the potential source.

Resistor **47**, connected between the gate and drain of FET transistor T3, provides negative feedback for the transistor. The larger the current flow through resistors **34** and **47**, the less the current flow through the transistor. Consequently, if capacitor **54** charges to a high potential, and a larger current flows through resistors **34** and **47** when the capacitor discharges, less current flows from the capacitor through transistors **T3**. On the other hand, if capacitor **54** charges to a lower level, when it discharges less current flows through resistors **34** and **47**, and consequently more discharge current flows from the capacitor through transistor **T3**. There are two discharge paths — one through resistors **34** and **47**, and the other through transistor T3 and resistor **47**. The two resistors and the transistor serve to maintain the total discharge current relatively constant independent of the initial potential across capacitor **54**. Thus the rate of change of the voltage across the capacitor during the discharge cycle is constant and independent of the initial battery voltage. This, in turn, implies that the drop in potential across the capacitor as a function of time is independent of the initial capacitor voltage, that is, the magnitude of the source potential. The provision of transistor T3 thus insures that the cut-off rate which determines when the pacer automatically switches to the continuous mode is stabilized and made independent of the source voltage.

While very high frequency signals have the same effect on capacitor **49** as 60-Hz signals, there is one type of signal which is not prevented from falsely operating transistors **T6** and **T10** by the lack of discharge of capacitor **49**. Specifically, single pulses of very narrow width can cause transistor T3 to conduct and a charging pulse to be delivered to capacitor **49**. If capacitor **49** is discharged at this time (as it would be before the end of each cycle) the positive step across capacitor **49** can falsely trigger transistors **T6** and **T10**. To preclude this possibility, resistor **45** is provided. Although each charging pulse causes a rapid rise in potential across capacitor **49**, the rise is not a perfect step function because resistor **45** increases the charging time constant. With a very narrow pulse, by the time capacitor **49** has begun to charge appreciably, the pulse terminates. Consequently, capacitor **49** does not charge sufficiently to trigger transistors **T6** and **T10**.

Transistors **T1** and **T2** serve a different function than transistors T3 and T4. The first two transistors, together with the various differentiators and integrators connected to them, serve as a frequency discriminator. Although higher frequencies are somewhat attenuated, it is the attenuation of the lower frequencies (below 20 Hz) which is of the utmost importance. By attenuating these signal frequencies and distinguishing between the different waves in the myocardial signal, it is possible to prevent triggering of transistors **T6** and **T10** by P and T waves. Although the frequency discrimination circuit attenuates signals below 20 Hz, this should not be confused with beats at a 72-per-minute rate. It is the emphasis on signal frequencies in the 20–30 Hz region which insures that beats at a 72-per-minute rate appear at the base of transistor T3 as a result of the R waves to the exclusion of other signals. As far as signals transmitted through capacitor **41** are concerned, it is more convenient to analyze the operation of the pacer in terms of activation rates. The frequency components in any particular signal are not determinative once the signal has been transmitted through capacitor **41.** From that point on, the important consideration is the number of activations of transistor T3 during any given period of time. It is the rate discrimination circuit which prevents cancellation of the pacer stimuli by competitive sine wave interference or any other interference from signals occurring at a rate greater than a minimum value. In the pacer of the drawing, interference is prevented for all signals occurring at a rate greater than 40 per second.

It is possible for the signal on electrodes E1 and E2 which results from the generation of an atrial stimulating pulse to be great enough such that after amplification transistor **T4** conducts. In such a case, the rise in potential across capacitor **49** would cause transistor **T6** to turn on and the ventricular timing circuit to be reset. For this reason, it is important to reduce the possibility of false triggering of transistor **T6.**

The short-duration (typically, 2-milliseconds) atrial stimulating pulse, even if it causes transistor T4 to conduct, causes the transistor to turn on only for 2 milliseconds. This short-duration pulse is similar to an RF spike which resistor **45** is designed to attenuate. Resistor **45** is included in the circuit so that capacitor **49** charges slowly with respect to the width of an RF spike. Only a relatively wide spike, such as that produced with the detection of a QRS waveform signal on electrodes E1 and E2, results in the charging of capacitor **59** to a sufficient level for triggering transistor **T6.** To further reduce the possibility of a spike resulting from the generation of an atrial stimulating pulse charging capacitor **49** to a level sufficient to trigger transistor **T6,** resistor **45** can be increased in magnitude. With a sufficiently large resistor, capacitor **49** can be prevented from charging sufficiently from a 2-millisecond spike to trigger the transistor. (If resistor **45** is too large, even a spike resulting from the detection of a QRS waveform signal may not charge capacitor **49** sufficiently to trigger transistor **T5.** This is due to the fact that with a large resistor **45** a small current flows for charging capacitor **49.** Thus even a spike resulting from the detection of a QRS waveform may not charge capacitor **49** sufficiently to trigger transistor T6 if resistor **45** is made too large.)

As described above, an important feature of the present invention is that even when the pacer operates in the continuous mode, each generation of a ventricular stimulating pulse causes the resetting of the atrial timing circuit. When a ventricular stimulating pulse is generated, capacitor **57** discharges through transistors **T7** and **T8.** At this time, these two transistors conduct current from the source, current flowing through potentiometer **34,** the two transistors, diode **40** and resistors **61** and **63.** It is the increased potential at the junction of resistors **61** and **63** which causes transistor **T9** to turn on. But the increased current flow also raises the potential of the emitter of transistor **T8.** The positive pulse is extended through diode **36** and resistor **38** to the base of transistor **T10.** Consequently, capacitor **58** discharges through transistor **T10** just as it does when the ventricular beat detecting circuit detects a spontaneous beat. Thus when the pacer operates in the continuous mode, both of capacitors **57** and **58** are discharged when a ventricular stimulating pulse is generated. Capacitor **57** discharges through transistors **T7** and **T8** to control the generation of the pulse in the first place, and capacitor **58** discharges through transistor **T10** just as it does when any ventricular beat (spontaneous or stimulated) is detected.

It should be noted that whenever transistor **T4** conducts and a positive pulse is transmitted through capacitor **53,** not only is the potential at the base of transistor **T6** raised but so is the potential at the base of transistor **T9** since the pulse at the base of transistor **T6** is applied across resistors **55, 61** and **63,** and the base of transistor **T9** is coupled to the junction of resistors **61** and **63.** Of course, when a ventricular beat is detected and transistor **T6** turns on to control the discharge of capacitor **57,** a ventricular stimulating pulse should not be generated. To prevent the conduction of transistor **T9** at this time, resistor **32** is provided. The resistor attenuates the magnitude of the pulse transmitted through capacitor **53** to a level sufficient to turn on transistor **T6** but insufficient to turn on transistor **T9.** Similarly, resistor **89** is provided so that the positive pulse transmitted through capacitor **54** to the base of transistor **T10** is sufficient in magnitude to turn on transistor **T10** and to discharge capacitor **58,** but is insufficient in magnitude to turn on transistor **T14** even though the pulse is extended to the base of this transistor through resistors **56, 64** and **66.**

It should also be noted that the purpose of the pulse transmitted through capacitor **54** is to turn on transistor **T10.** In the absence of diode **36,** it is possible for current to flow through resistor **38,** diode **40,** and resistors **61** and **63.** This would attenuate the magnitude of the pulse supplied to the base of transistor **T10.** Diode **36** is provided for isolation purposes; when a pulse is extended through capacitor **54** to the base of transistor **T10,** no current is diverted through resistor **38.** In effect, diode **36** allows the conduction of transistors **T7** and **T8** to cause a pulse to be extended to the base of transistor **T10** for controlling the discharge of capacitor **58,** without allowing the attenuation of a pulse transmitted through capacitor **54** for the same purpose.

Although the invention has been described with reference to a particular embodiment, it is to be understood that this embodiment is merely illustrative of the application of the principles of the invention. Numerous modifications may be made therein and other arrangements may be devised without departing from the spirit and scope of the invention.

What I claim is:

1. An atrial and ventricular pacer comprising ventricular electrode means, atrial electrode means, means for supplying a ventricular stimulating pulse to said ventricular electrode means at the end of a first timing period, means for supplying an atrial stimulating pulse to said atrial electrode means at the end of a second timing period, first means for detecting a beating action of said patient's heart and responsive thereto for re-starting said first and second timing periods, means for disabling said detecting means, and second means responsive at least during the operation of said disabling means and to the operation of said ventricular pulse supplying means for re-starting said first and second timing

2. An atrial and ventricular pacer in accordance with claim **1** further including voltage supply means connected to and for energizing at least one of said atrial and ventricular pulse supplying means, said pulse supplying means including a charging circuit having a capacitor and means for charging said capacitor from said voltage supply means, means for deriving a reference potential, means for controlling the supply of a pulse to the respective electrode means when the voltage across the capacitor reaches said reference level, and means for varying the reference level in accordance with the potential of said voltage supply means and for charging said capacitor from an initial level to said reference level in a time substantially independent of the potential of said voltage supply means.

3. An atrial and ventricular pacer in accordance with claim **2** wherein said reference level varying means includes means maintaining the ratio of the potential of said voltage supply means to the magnitude of said reference level substantially constant independent of the potential of said voltage supply means.

4. An atrial and ventricular pacer in accordance with claim **1** further including voltage supply means having two terminals, said detecting means including a first amplifying stage coupled to said ventricular electrode means, a second amplifying stage for amplifying the output signal of said first amplifying stage, means for energizing both of said first and second amplifying stages from said two terminals, and means for deriving a biasing potential for said first amplifying stage from said second amplifying stage.

5. An atrial and ventricular pacer in accordance with claim **1** including capacitor means, means for charging said capacitor means to an initial value responsive to the operation of said detecting means, means for discharging said capacitor means following the charging thereof, means responsive to an incremental increase in voltage across said capacitor means which exceeds a predetermined value when said capacitor means is charged by said charging means for operating said first re-starting means, and means for controlling said discharging means to discharge said capacitor means at a rate which is independent of said initial value.

6. An atrial and ventricular pacer in accordance with claim **5** wherein said discharge controlling means includes means for causing a substantially constant discharge current to flow from said capacitor means.

7. An atrial and ventricular pacer comprising ventricular electrode means, atrial electrode means, means for supplying a ventricular stimulating pulse to said ventricular electrode means at the end of a first timing period, means for supplying an atrial stimulating pulse to said atrial electrode means at the end of a second timing period, first means for detecting a beating action of said patient's heart and responsive thereto for restarting said first and second timing periods, means for disabling said detecting means, and second means responsive at least during the operation of said disabling means and to the termination of said first timing period for re-starting said second timing period.

8. An atrial and ventricular pacer in accordance with claim **7** including capacitor means, means for charging said capacitor means to an initial value responsive to the operation of said detecting means, means for discharging said capacitor means following the charging thereof, means responsive to an incremental increase in voltage across said capacitor means which exceeds a predetermined value when said capacitor means is charged by said charging means for operating said first re-starting means, and means for controlling said discharging means to discharge said capacitor means at a rate which is independent of said initial value.

9. An atrial and ventricular pacer in accordance with claim **8** wherein said discharge controlling means includes means for causing a substantially constant discharge current to flow from said capacitor means.

10. A timing circuit for a heart pacer, said pacer including means for detecting a beating of said patient's heart and means for disabling said detecting means, said circuit comprising voltage supply means, a charging circuit having a capacitor and means for charging said capacitor from said voltage supply means, means for deriving a reference potential, means for determining the end of a predetermined time interval when the voltage across the capacitor reaches said reference level, means for varying the reference level in accordance with the potential of said voltage supply means, said capacitor charging means charging said capacitor from an initial level to said reference level in a time substantially independent of the potential of said voltage supply means during operation of said detecting means, and in a time substantially dependent on the potential of said voltage supply means during operation of said disabling means.

11. A timing circuit for a heart pacer in accordance with claim **10** wherein said reference level varying means includes means for maintaining the ratio of the potential of said voltage supply means to the magnitude of said reference level substantially constant independent of the potential of said voltage supply means.

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