July 1, 1969 H. R. GUARINO 3,452,739

HEART PUMP SYNCHRONIZING APPARATUS

Filed Aug. 15, 1966 Sheet 1 of 2

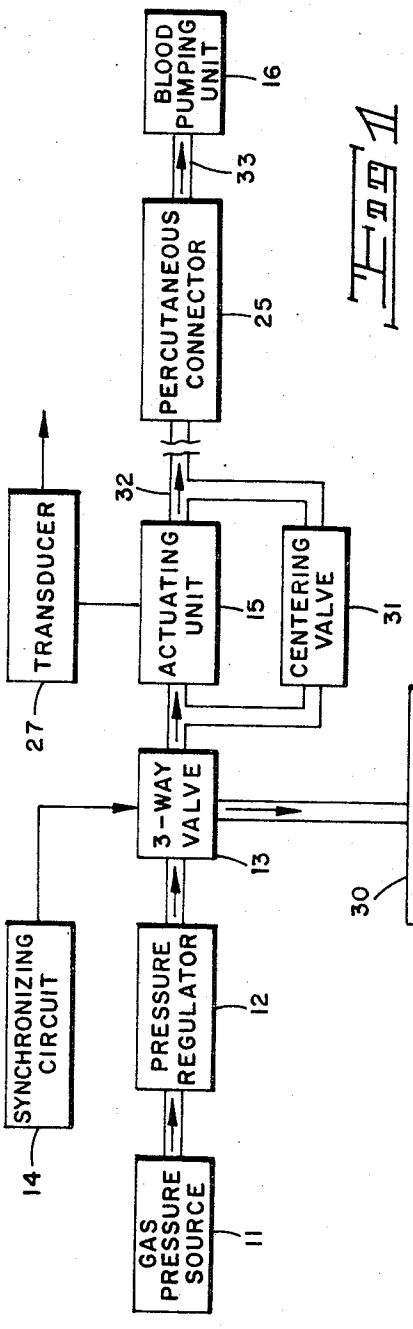


FIG. 1

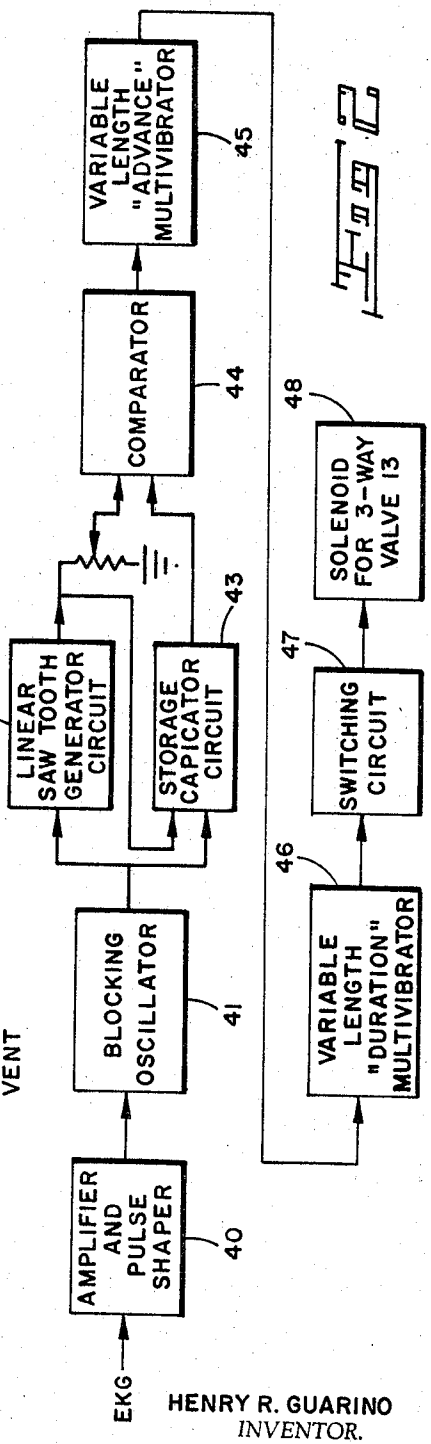


FIG. 2

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HEART PUMP SYNCHRONIZING APPARATUS

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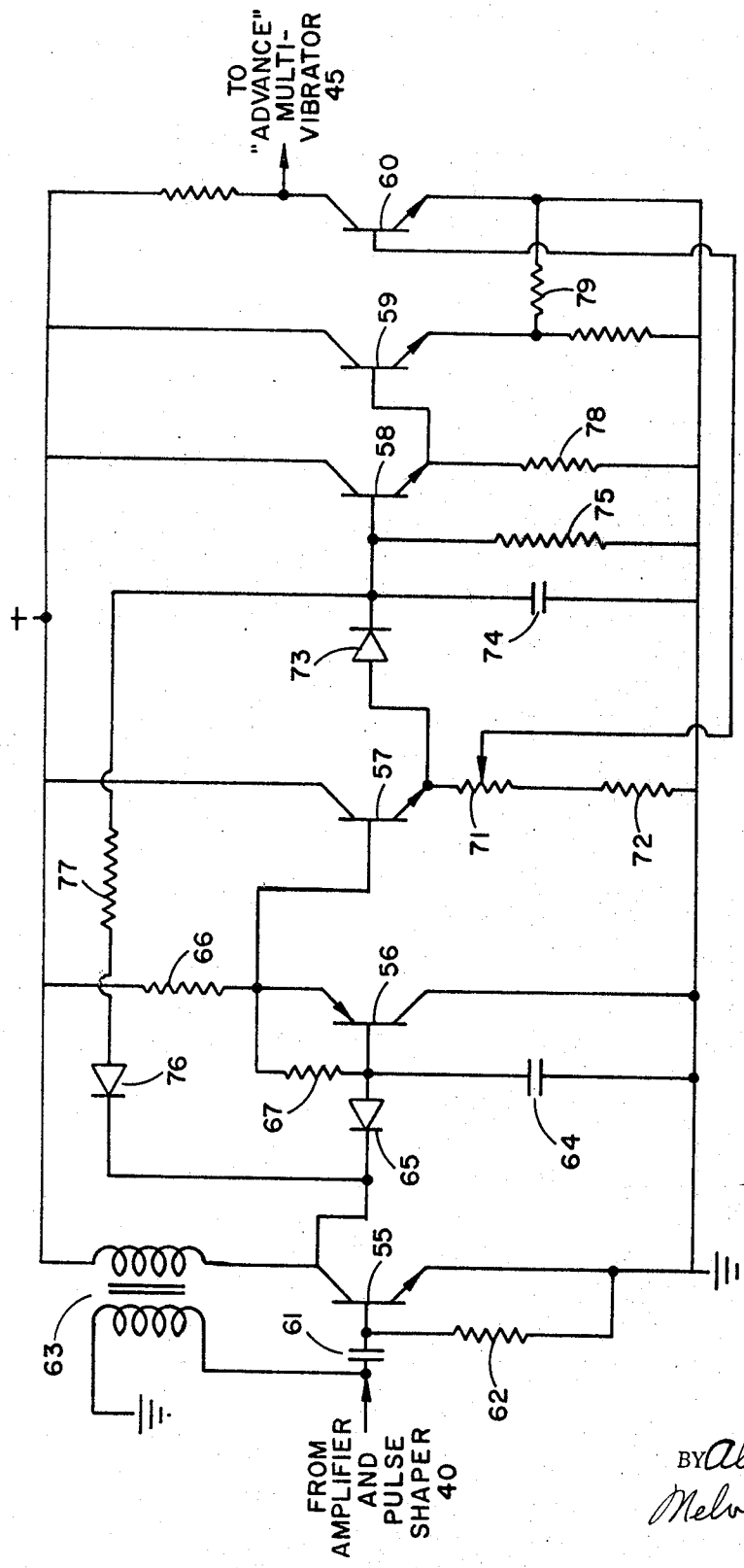


FIG. 5

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HEART PUMP SYNCHRONIZING APPARATUS

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Int. Cl. A61m 1/03
U.S. Cl. 128—1 8 Claims

ABSTRACT OF THE DISCLOSURE

A synchronizing circuit for circulatory assist systems that follows the patient's heart beat. The patient's R-wave is used to actuate a saw tooth generator which charges a capacitor which is also partially discharged by signals derived from the R-wave. The output signal of the saw tooth generator and the voltage across the capacitor are compared to provide a second signal prior to the arrival of the next succeeding R-wave. This second signal trips a one shot multivibrator which in turn trips a second one shot multivibrator stable in one direction for a selectable time interval whereby the diastolic phase of the blood pumping unit is adjustably caused to effectively begin with the systolic phase of the patient's heart and terminate at a selectable subsequent time interval.

This invention relates to heart pump apparatus and more particularly to apparatus for synchronizing circulatory assist systems wherein a blood pumping unit is synchronized with the demands of a patient's heart.

The advent of open heart surgery has presented to the medical profession the opportunity of repairing damaged or diseased hearts of individuals and where appropriate, using circulatory assist systems in individuals who without such correction and/or systems face premature death. Many devices are involved in this type of surgery. For example, one circulatory assist system may comprise a valveless blood pump connected across the arch of the aorta and driven by fluid pressure in response to electronic signals (QRS wave) provided by the heart itself. By operating the blood pumping unit in proper phase, the systolic pressure in the left ventricle can be reduced and the systemic circulation can be maintained with a substantially reduced work load on the heart muscle. In addition, the operation of the blood pumping unit has the effect of shifting the phase of the normal systolic pressure so that this pressure appears in the aorta at a time when the left ventricle is relaxed. Assuming competence of the normal aortic valve, one then has an increased perfusion pressure available to the coronary arteries. It is believed that such an increase in coronary perfusion, together with a reduction in the effort required from the heart, should be effective in a number of cases of cardiac insufficiency.

As may be seen from the above, the blood pumping unit must be capable of being synchronized with the patient's heart and, accordingly, an important component of circulatory assist systems is electrically operated synchronizing or control means for synchronizing or controlling operation of the blood pumping unit.

By using heart pump equipment for extended periods of time, it is contemplated that the equipment may be utilized for regional perfusions in therapeutic treatment of the heart. Still other use of the equipment will be to provide circulation of blood through an artificial organ such as an external artificial kidney. In connection with this function of the apparatus, it should be noted that many research institutions at this time are concentrating their research activities on providing artificial counterparts of other organs and whenever such application requires circulation, the present invention may be utilized.

Implantable prior art pulsatile pumps usually consist of

a flexible bulb or ventricle squeezed by pressurized fluids from a pumping or actuating unit and is coupled to one or more blood vessels such as arteries or veins. Generally, arterial graft sections connect the bulb to the circulatory system. These arterial graft sections are generally of the woven Teflon type or Dacron type employed in the insertion of arterial grafts and the replacement of damaged sections of an artery. Edwards Seamless Arterial Graft manufactured by the United States Catheter and Instrument Company have been found to be satisfactory.

In most, if not all, circulatory assist systems, it is necessary as noted above that the flexible bulb be synchronized with the patient's heart. A typical pneumatically driven and electrically controlled circulatory assist system is broadly disclosed in U.S. Patent No. 3,099,260. Other systems are disclosed in patent application No. 355,273 filed Mar. 27, 1964, and patent application No. 531,281 filed Mar. 2, 1966, to which reference is made and which are assigned to the same assignee as this application.

In the use of circulatory assist systems, which, for example, utilize a valveless blood pumping unit, it is necessary that during its systolic stroke the heart fill the blood pumping unit and that accordingly, the filling or diastolic stroke of the pumping unit be actuated in phase with the systolic stroke of the patient's heart.

In accordance with the preferred embodiment of the invention, signals derived from the R-wave actuate a linear saw tooth generator that provides a linearly increasing voltage which charges a storage capacitor which in turn is partially discharged by the said signals derived from the R-wave. The saw tooth voltage and voltage across the storage capacitor are compared in a comparator to provide a second signal at a selectable time interval prior to the arrival of the next succeeding R-wave, and the second signal trips a one shot multivibrator which in turn trips a second one shot multivibrator stable in one direction for a selectable time interval whereby the diastolic phase of the blood pumping unit is adjustably caused to effectively begin with the systolic phase of the patient's heart and terminate at a selectable subsequent time interval. Accordingly, an object of the present invention is the provision of means for synchronizing a blood pumping unit with a patient's heart.

Another object is the provision in a circulatory assist system of a synchronizing circuit that is actuated by the R-wave from a patient's heart.

A further object is the provision in a circulatory assist system of a synchronizing circuit which follows the heart beat of a patient.

A still further object is the provision in a circulatory assist system for controlling the operation of a blood pumping unit of a synchronizing circuit which provides an output signal phased with the R-wave of the patient's heart and determined by the time interval between previous R-waves.

A still further object is the provision in a circulatory assist system of a synchronizing circuit for providing output pulses which follow changes in a patient's heart beat and which have an adjustable time interval with respect to a succeeding R-wave.

The novel features that are considered characteristic of the present invention are set forth in the appended claims; the invention itself, however, both as to its organization and method of operation together with additional objects and advantages thereof, will best be understood from the description of a specific embodiment when read in conjunction with the accompanying drawings, in which:

FIGURE 1 is a block diagram of a typical circulatory assist system;

FIGURE 2 is a block diagram of electrical components in accordance with the invention comprising the synchronizing circuit of FIGURE 1; and

FIGURE 3 is a schematic diagram showing details of electrical components shown in FIGURE 2.

Directing attention now to FIGURE 1, there is shown a schematic illustration of a typical heart pumping or circulatory assist apparatus intended to provide intercorporeal mechanical assistance. As shown in FIGURE 1, in a typical system a suitable pressurized source of gas **11** feeds into a low pressure regulator **12**. Large oxygen bottles which area readily available and are a satisfactory source of oxygen are generally pressurized to a pressure of several thousand pounds and generally have a pressure regulator which, while not particularly sensitive, is satisfactory to provide a reduction in pressure approaching that required for the actuation of the blood pumping unit. A satisfactory pressure for the pumping unit has been found to be approximately 3 pounds per square inch; hence, pressure regulator **12**, while of conventional design, should permit small adjustments in the pressure range of about 10 to 3 pounds per square inch. The output of the low pressure regulator **12** is fed to a three-way solenoid actuated valve **13**. The valve **13**, which is normally connected to pressure, is adapted to be operated by a synchronizing circuit **14** and allows actuating unit **15** to be alternately connected to pressure and vented. Thus, only when the valve **13** is actuated by the synchronizing circuit **14** does the valve **13** cut off the supply of compressed gas to the actuating unit **15** which in turn controls the action of the pumping unit **16**.

Directing attention now to the actuating unit **15**, it may be the type disclosed in the aforementioned patent but is preferably of the type comprising a low inertial diaphragm separating the unit into an input compartment and an output compartment, the pressurized gas from valve **13** being admitted into the input compartment and the gas in the output compartment being in communication with the pumping unit **16** through pressure line **32**, a percutaneous connector **25** and pressure line **33**. The actuating unit preferably is provided with an adjustable stop to prevent the diaphragm from providing a volumetric displacement greater than a preselected amount and in any event not greater than about 60 cc. which is in the range of the average volumetric displacement of the left ventricle of the human heart. Further, the actuating unit should have a low resistance to maintain the load on the heart as low as possible since the heart must move the diaphragm unless the input compartment is coupled at the appropriate time to an appropriate back pressure through valve **13** during diastole.

Mounted or affixed to the actuating unit **15** is a transducer **27** actuated by actuating unit **15**. This may be accomplished in conventional fashion, for example, by providing a mechanical connection such as a rod between the transducer **27** and the aforementioned diaphragm in the actuating unit **15**. While the particular type of transducer used is not critical, it should preferably provide a direct current signal, the magnitude and polarity of which is representative of the movement of the diaphragm. Thus, if the diaphragm is moving, the output signal of the transducer **27** will be a varying but unidirectional signal, if the diaphragm stops in any particular place, the output signal will be a direct current voltage, when the diaphragm reaches one end of its travel, the output signal will be of a maximum value of given polarity, and when the diaphragm reaches the other end of its travel, the output signal will again be of a maximum value but of opposite polarity. For a more complete discussion of a suitable actuating unit, reference is made to patent application Ser. No. 568,248, filed July 27, 1966 by Michael L. Rishton and assigned to the same assignee.

A typical pumping unit comprises a rigid case containing a collapsible bulb, the outer surface of which is in communication with a pressurized gas (the output compartment of the pumping unit **15**) and the inner surface of which is in communication with the circulatory system of a body. A typical extracorporeal ventricle is disclosed in the aforementioned U.S. Patent No. 3,099,260 and a typical intercorporeal ventricle is disclosed in the aforementioned patent application Ser. No. 355,273.

By way of example, the rod actuated by the diaphragm may be movable into and out of a coil to vary the output frequency of an oscillator which is rectified to provide either a constant direct current signal or a varying direct current signal, depending on the movement of the diaphragm.

Since the zero position of a low inertia diaphragm can move or be made to move because, for example, of a slow leak, changes in pressure, diffusion of the gas through the bulb and/or tubing and the like, an adjustable centering valve **31** coupling the input compartment and the output compartment of the pumping unit is provided for centering and/or recentering of the diaphragm. Centering valve **31** may comprise a conventional manually or automatically adjustable valve to provide the desired flow rate between the input compartment and the output compartment when a difference of pressure exists between them. Such an arrangement or its equivalent is essential to insure that a given volumetric displacement in the actuating unit **15** is reflected in the pumping unit **16**.

Attention is directed to the fact that three-way valve **13** is vented to atmosphere through diastolic back-pressure producing means **30**. Means **30** may comprise, for example, a volume large with respect to the volumetric displacement of actuating unit **15** and an adjustable needle valve or the like (not shown) to permit controlled venting of actuating unit **15** and thereby provide a back pressure substantially equal to the diastolic pressure of the patient. The provision of a diastolic back pressure is essential to insure that output signal of transducer **27** is representative of diastole in the patient. It has been found that if diastolic back-pressure producing means **30** is not provided, not only will back flow of blood into the pumping unit **16** occur, but during diastole the diaphragm now actuated by the diastolic pressure in the circulatory system will be permitted to move at a rate not representative of pressure in the circulatory system during diastole. This has the added disadvantage of resulting in undue wear on the bulb by permitting it to strike the case at the end of its diastolic stroke.

All of the foregoing components with, of course, the exception of the percutaneous connector and pumping unit may be located in a bedside control panel. Tube **32** connects the pneumatic portion of the system to the patient in which is implanted the percutaneous connector **25** and the pumping unit **16**. Tube **33** which is disposed interior of the body connects the percutaneous connector to the pumping unit.

Broadly, the action of both the actuating unit and the pumping unit must be capable of being synchronized with the patient's heart. The actuating unit and hence the pumping unit must be capable of being phased with the patient's heart while the duration of the systolic and diastolic strokes should be adjustable. The synchronizing circuit **14** performs the function of properly synchronizing the operation of the solenoid in valve **13** for admitting the pressurized gas into the actuating unit **15** in accordance with the demands of the patient. Typically, the synchronizing circuit is actuated by the patient's electrocardiogram or the R-wave (not shown) taken directly from his heart. By way of example, the output of an EKG unit may be fed into an amplifier and synchronizer pulse shaper circuit that is adapted to amplify the sync pulse or electrical signal used for synchronizing purposes. The amplifier and synchronizing pulse shaper may be designed not only to limit the magnitude of the sync pulse but also to shape it. The actuating unit is preferably synchronized with the R-wave portion of the sync pulse and all other portions of the wave may accordingly either be reduced or removed, thereby leaving only the R-wave. Since the hydraulic events in the patient's heart are not simultaneous with the EKG unit or the R-wave and, furthermore, since

the hydraulic events in the patient's circulatory system are delayed behind the systolic pulse of the heart by varying amounts depending on the distance of the artery or vein from the left ventricle of the heart, it is desirable to provide means for phasing the systolic or the diastolic pulse of the pumping unit as the case may be with the systolic pulse of the heart in order to accommodate these time delays and provide the desired time delay.

For the system shown in FIGURE 1, in accordance with the present invention, a network triggered by the R-wave is provided to create a sync pulse delayed behind the actuating R-wave and preceding the next succeeding R-wave by a controlled amount to enable the diastolic pulse of the pumping unit to controllably correspond with the systolic pulse of the patient's heart. By providing means for initiating the diastolic pulse of the pumping unit a controllable time interval prior to the beginning of the heart's systolic pulse (because of time delays inherent in all mechanical systems) and terminating the diastolic pulse of the pumping unit a controllable time interval after it has been initiated, the pumping unit may be satisfactorily phased with the events in the circulatory system of substantially any patient. Further, the time constant of the delay network (exclusive of any manual adjustment) is dependent on the time interval between a plurality of prior R-waves, typically one to about five. Accordingly, even though a patient's heart beat may vary from its normal rate to, for example, a higher rate, the time at which the diastolic pulse of the pumping unit is initiated will, except for arrhythmia and/or high rates of change, occur at substantially the same time interval prior to the next succeeding R-wave.

Directing attention now to FIGURE 2, which shows details of the synchronizing circuit **14** of FIGURE 1, the output of an EKG unit, or preferably the R-wave taken directly from the patient's heart (not shown) comprising a synchronizing signal is fed to an amplifier and pulse shaper circuit **40** of conventional design to provide an output signal representative of the R-wave. Accordingly, the amplifier and pulse shaper circuit **40** may in conventional manner limit the amplitude of the synchronizing signal and reduce or remove all portions of this signal other than the R-wave whereby only that portion of the signal representative of the R-waves is supplied to a conventional blocking oscillator **41**. The output of oscillator **41** are sharp narrow pulses of a predetermined and constant magnitude which coincides with the R-waves of the synchronizing signal.

The output of the blocking oscillator **41** is fed simultaneously to a linear saw tooth generator **42** and a storage capacitor circuit **43** described in greater detail hereinafter. The output of the linear charging circuit **41** is a linear ramp or saw tooth wave and the output of the storage capacitor circuit **43** is a wave having a short rise time and small drop-off after reaching its maximum amplitude. The storage capacitor circuit **43** is charged by the linear saw tooth generator **42** and the output of blocking oscillator **41** functions to at least substantially discharge the linear saw tooth generator circuit **42** and partially discharge the storage capacitor circuit **43** whereby both circuits are actuated simultaneously upon arrival of an R-wave and the amplitude of their output signals is proportional to the frequency of the incoming R-waves.

The output signals of the aforementioned circuits are fed to a comparator **44** which may include an amplifier to provide a sharp narrow pulse when the amplitude of the output signals of the two circuits are equal. The amplitude of the output signal from the linear saw tooth generator circuit **42** or alternately, the output signal of the storage capacitor circuit **43** may be continuously varied to permit actuation of comparator **44** at some preselected time interval prior to the next succeeding R-wave. Assuming that the R-wave frequency remains fixed, the amplitude and wave form of the storage capacitor circuit, for example, remains fixed and is triggered as is the linear saw tooth generator circuit by each R-wave as described hereinabove. Accordingly, manual variation of the amplitude of, for example, the output of the linear saw tooth generator circuit will result in triggering of the comparator from substantially any time shortly after arrival of a triggering R-wave to the arrival of the next succeeding R-wave. The output signal of the comparator **44** is fed to a first or "advance" variable length one shot multivibrator **45** which is stable in one direction and is tripped into its other mode of operation by the output signal of the comparator. While the output signal of the comparator can theoretically be used directly to determine the advance necessary to initiate action of three-way valve **13** (see FIGURE 1), use of the "advance" multivibrator **45** to establish the amount of advance is preferred because of, among other things, the sensitivity required of the advance adjustment. Further, as more fully described hereinbelow, the advance multivibrator **45** permits an advance as well as a delay, with respect to a succeeding R-wave, of initiating action of three-way valve **13**.

Assuming that the comparator **44** is actuated sufficiently in advance of the next succeeding R-wave, as has been found to be easily attainable, multivibrator **45** may be provided with a variable RC circuit to permit adjustment of the time it remains in its tripped condition. Thus, differentation of the output pulse of multivibrator **45** will provide two pips the first of which corresponds with the leading edge of the differentiated output pulse and the second of which corresponds with the trailing edge of the differentiated output pulse and which is fed to a second or "duration" multivibrator **46**. The "duration" multivibrator **46** is substantially identical to the "advance" multivibrator **45** and is tripped by the termination of the output pulse of the "advance" multivibrator **45**. The "duration" multivibrator **46** may also be provided with a variable RC circuit to permit adjustment of the time that the three-way valve **13** is actuated which is to say vented and thereby determine the diastolic pulse of the pumping unit **16**. The output of the "duration" multivibrator **46** is fed to a conventional switching circuit **47** comprising the solenoid **48** of the three-way valve **13**. Thus, when switching circuit **47** is actuated, the circuit supplying current to the solenoid **48** of the three-way valve **13** is broken and the actuating unit **15** is vented.

Attention is now directed to FIGURE 3 which shows details of the blocking oscillator, saw tooth generator circuit, storage capacitor circuit and the comparator discussed in connection with FIGURE 2. As shown in FIGURE 3, the output signal from the amplifier and pulse shaper **40** is coupled to blocking oscillator **41** comprising transistor **55**, capacitor **61**, resistor **62** and feed back transformer **63**. The emitter electrode of transistor **55** is connected to ground, resistor **62** is connected between the emitter and base electrode of transistor **55**, and the primary winding of transformer **63** is connected between B+ and the collector electrode whereby a portion of the output signal at the collector electrode is coupled back to the base electrode in conventional manner. The input signal to transistor **55** may be of the order of three or four volts and the output signal of transistor **55** (which is a sharp negative going signal for the embodiment shown) is used primarily to discharge the ramp capacitor **64** forming part of the saw tooth generator circuit **42**. The output signal from transistor **55** is taken at its collector electrode and coupled to the base electrode of transistor **56** through a diode **65**. The collector electrode of transistor **56** is connected to ground, the emitter electrode being connected to B+ through a resistor **66** and to the base electrode through resistor **67**. Capacitor **64** is connected between the base and collector electrodes of transistor **56**. Transistor **56** and its associated resistors comprise a "boot-strap" circuit the function of which is to cause capacitor **64** to charge linearly through transistor **56** in the absence of an output signal from transistor **55**. Accordingly, when an R-wave (or an electric

signal derived therefrom) is coupled to transistor 55, it fires and its output signal coupled through diode 65 very quickly substantially completely discharges the capacitor 64. After the output signal from transistor 55 disappears, capacitor 64 begins to again charge up linearly through transistor 56 and its emitter resistors until it is discharged by the next pulse from transistor 55. The function of diode 65 is to couple the output signal from transistor 55 to capacitor 64 and in the interim prevent capacitor 64 from discharging into the collector electrode of transistor 55. It should be noted at this point that the plate side of diode 65 is connected to B+ whereas the cathode side is connected to capacitor 64. Accordingly, capacitor 64 continually tries to charge linearly to B+, but when the negative output signal from transistor 55 is coupled to capacitor 64, the voltage on capacitor 64 drops rapidly to essentially zero. Thus, as will now be seen, in the boot-strap circuit disclosed hereinabove, capacitor 64 is linearly charged through transistor 55 and is very rapidly discharged through diode 65 to provide a linear saw tooth voltage the frequency of which corresponds to the frequency of the R-waves coupled to transistor 55. The aforementioned linear saw tooth voltage appears across emitter resistor 66 and is coupled directly to the base electrode of transistor 57 which comprises an emitter follower. Transistor 57 functions in conventional manner to provide a high input impedance to prevent distortion of the signal at the emitter electrode of transistor 56 and a very low output impedance at its emitter electrode. The linear saw tooth voltage appearing at the emitter resistor 66 is coupled through transistor 57 and appears across emitter resistors 71 and 72 connected between the emitter electrode of transistor 57 and ground. Resistor 71 is provided with an adjustable tap to permit a portion of the linear saw tooth voltage appearing at the emitter electrode of transistor 57 to be coupled to the base electrode of transistor 60 as and for the purposes hereinafter described. The output signal of transistor 57 is taken from its emitter electrode and is coupled through diode 73 to capacitor 74 and the base electrode of transistor 58. Diode 73 is poled to prevent capacitor 74, which is preferably a storage capacitor, from discharging through resistors 71 and 72 which may have a total resistance of about five thousand ohms. Diode 76 and resistor 77, which are connected between the collector electrode of transistor 55 and capacitor 74, function to partially discharge capacitor 74 when an output signal appears at the collector electrode of transistor 55. Resistor 77 preferably is adjusted or chosen whereby when an output signal appears at the collector electrode of transistor 55, only a small portion such as, for example, ten to fifteen percent of the charge stored in capacitor 74 will be discharged through this portion of the storage capacitor circuit. The storage capacitor circuit 43 comprises capacitor 74, diode 76 and resistor 77. Capacitor 74 is charged by the saw tooth output voltage of transistor 57 and is partially discharged through substantially only resistor 77 and diode 76. The voltage across capacitor 74 varies essentially exponentially within relatively small limits and is coupled through transistor 58 to transistor 59. Transistor 58 together with resistors 75 and 78 comprises an emitter follower which functions to provide a high input impedance (a high impedance across capacitor 74 as resistor 75 is selected to have a high resistance) and a low output impedance (a low impedance at its emitter electrode) for driving transistors 59 and 60 which comprise the comparator circuit 44.

As will now be apparent, for a given R-wave frequency, the voltage across capacitor 64 will be a saw tooth that varies linearly from zero to some plus value and the voltage across capacitor 74 will vary exponentially. Whereas the amplitude of the voltage across capacitor 64 increases linearly from zero after receipt of an R-wave, the voltage across capacitor 74 will simultaneously rise very quickly from some value slightly less than its maximum value and thereafter drop off very slowly, the maximum amplitude of both voltages being essentially determined by the time interval between one or more preceding R-waves. Further, whereas the charge on capacitor 64 is essentially completely dissipated upon receipt of each R-wave, the charge on capacitor 74 is only partially removed.

For the embodiment shown in FIGURE 3, transistors 59 and 60 comprise a comparator circuit. Transistors 59 and 60 are connected in conventional manner as shown to form a well known comparator circuit with the exception that transistor 59 is connected to provide an output impedance at its emitter electrode that is even lower than the output impedance at the emitter electrode of transistor 58. As compared to the amplitude of the linear saw tooth voltage at the emitter of transistor 57, the amplitude of the signal at the emitter electrode of transistor 59 is reduced. By way of example, one may expect a voltage drop of about 0.6 volt across respectively diode 73, transistor 58 and transistor 59.

Accordingly, at the emitter electrode of transistor 60, the voltage at this point may be expected to be approximately one and one-half to two volts less than that at the emitter electrode of transistor 57. As will now be apparent, the amplitude of the voltage coupled from the emitter electrode of transistor 59 through resistor 79 to the emitter electrode of transistor 60 is essentially equal to the peak value of the saw tooth voltage at the emitter electrode of transistor 57 minus approximately one and one-half volts. The saw tooth voltage is coupled to the base electrode of transistor 60 from resistor 71 in the emitter circuit of transistor 57. It is necessary that the amplitude of the linear ramp voltage supplied to the base electrode of transistor 60 be made adjustable so that the amplitude of the saw tooth voltage and the storage capacitor voltage will coincide at some predetermined and selectable time prior to the arrival of the next succeeding R-wave, and provide an output pulse at the collector electrode of transistor 60.

The output signal of transistor 60 is a signal which rises rather slowly and for this reason may be coupled to one or more amplifiers (not shown) prior to coupling it to the "advance" multivibrator 45 to provide a fast rising signal having an amplitude of, for example, five to six volts. As discussed in connection with FIGURE 2, this signal is used to trigger the variable length advance multivibrator 45 which essentially determines when the actuating unit will be vented to atmosphere.

The provision of a saw tooth generator circuit and a storage capacitor circuit as described hereinabove is particularly advantageous in that it permits the comparator circuit to be triggered sufficiently in advance of the next succeeding R-wave to permit the provision of "advance" multivibrator 45, the pulse length of which can be selected to provide either an advance or delay, as compared to the next expected R-wave of the systolic pulse of the actuating unit. As previously described, multivibrator 46 determines the length of the systolic pulse of the actuating unit. Further, because of the partial discharge of capacitor 74, even in the presence of a rapid change in frequency of the patient's R-wave, the described circuits automatically provide advance actuation of the actuating unit at the preset time interval within a matter of only a few heart beats.

The various features and advantages of the invention are thought to be clear from the foregoing description. Various other features and advantages not specifically enumerated will undoubtedly occur to those versed in the art, as likewise will many variations and modifications of the preferred embodiment illustrated, all of which may be achieved without departing from the spirit and scope of the invention as defined by the following claims.

What is claimed is:

1. In a circulatory assist system including means for producing an electric signal that is a direct function of the pumping action of the patient's heart, an actuating unit and a blood pumping unit controlled by said actuating unit, the combination comprising:

(a) first and second charging circuit means, said second charging circuit means being charged through said first charging circuit means and attains and substantially retains its maximum charge substantially prior to that of said first charging circuit means;

(b) means for coupling said electrical signal to said first and second charging circuit means; and

(c) means for controlling the operation of said actuating means in response to the output signals of said first and second charging circuit means for phasing the systolic pulse of said actuating unit with the diastolic pulse of the patient's heart.

2. The combination as defined in claim 1 wherein said first charging circuit means comprises a linear saw tooth generator and said second charging circuit means includes a storage capacitor circuit.

3. The combination as defined in claim 2 wherein said means for coupling said electrical signal to said first and second charging circuits means includes first means for substantially completely discharging said first charging circuit means and second means for only partially discharging said second charging circuit means when said first charging circuit means is discharged.

4. In a synchronizing circuit in a circulatory assist system for synchronizing the pumping action of an actuating unit which controls the action of a blood pumping unit with the pumping action of the patient's heart wherein said synchronizing circuit is responsive to the patient's R-wave, the combination comprising:

(a) means for providing an electric signal that is a direct function of the patient's R-wave;

(b) a first charging circuit for providing a linear saw tooth output signal;

(c) a second charging circuit coupled to the output of and charged by said first charging circuit;

(d) first means for coupling said electric signal to said first and second charging circuits whereby said first and second charging circuits are simultaneously discharged in synchronism with the patient's R-wave, said first circuit being substantially discharged but said second circuit being only partially discharged; and

(e) second means for controlling the operation of said actuating means in response to the output signals of said first and second charging circuit means for phasing the systolic pulse of said actuating unit with the diastolic pulse of the patient's heart.

5. The combination as defined in claim 4 wherein the time constant of said second charging circuit is short compared to that of said first charging circuit and additionally including third means for varying the amplitude of the output signal of one of said charging circuits whereby the amplitude of said saw tooth signal equals the amplitude of the output signal of said second charging circuit prior to the next succeeding R-wave.

6. The combination as defined in claim 5 wherein said second charging circuit includes a storage capacitor coupled to the output of said first charging circuit and said first means includes a diode and resistor coupled between said storage capacitor and the output of said means for providing said electric signal.

7. The combination as defined in claim 5 wherein said second means includes:

(a) comparator circuit means for providing an output signal when the amplitude of the output signals of said first and second charging circuits are equal;

(b) a first one-shot multivibrator triggered by the output of said comparator circuit means, said first multivibrator including means for controlling the time it remains in its triggered condition; and

(c) a second one-shot multivibrator triggered by the output of said first multivibrator, said second multivibrator including means for controlling the time it remains in its triggered condition.

8. The combination as defined in claim 7 wherein said second means additionally includes a solenoid that is responsive to the output signal of said second multivibrator to control a valve, said valve directing an operating medium into said actuating unit for causing the operation thereof.

References Cited

UNITED STATES PATENTS

3,099,260	7/1963	Birtwell	128—1
3,266,487	8/1966	Watkins et al.	128—1

DALTON L. TRULUCK, *Primary Examiner.*

U.S. Cl. X.R.

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