March 9, 1971 F. R. GOLDSCHMIED 3,568,214

ARTIFICIAL HEART SYSTEM AND METHOD OF PUMPING BLOOD BY ELECTROMAGNETICALLY PULSED FLUID

Filed July 24, 1968 2 Sheets-Sheet 1

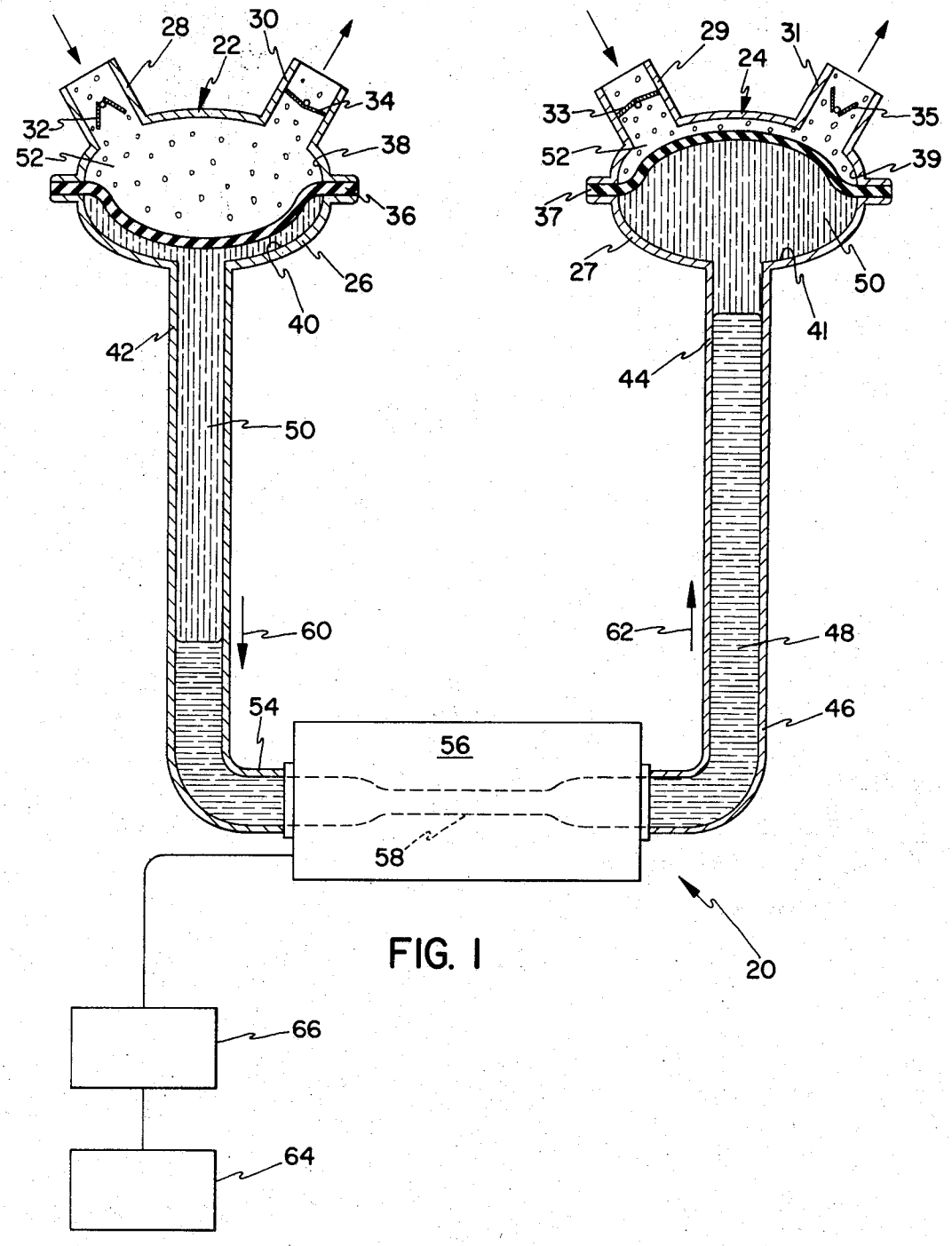

FIG. 1

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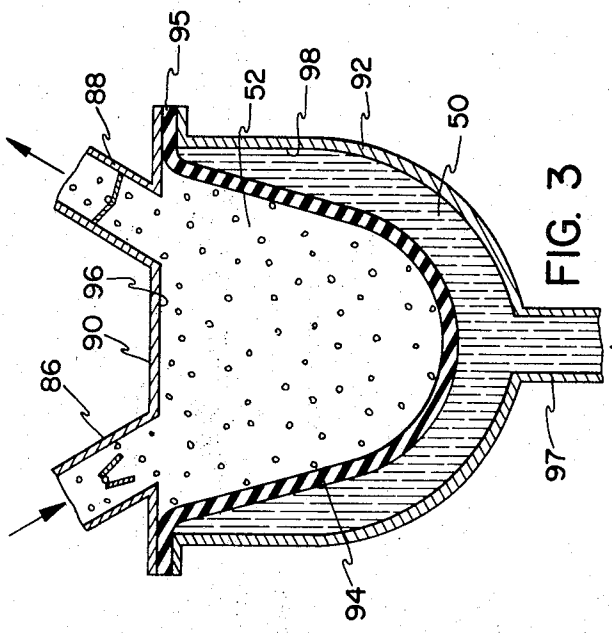

FIG. 3

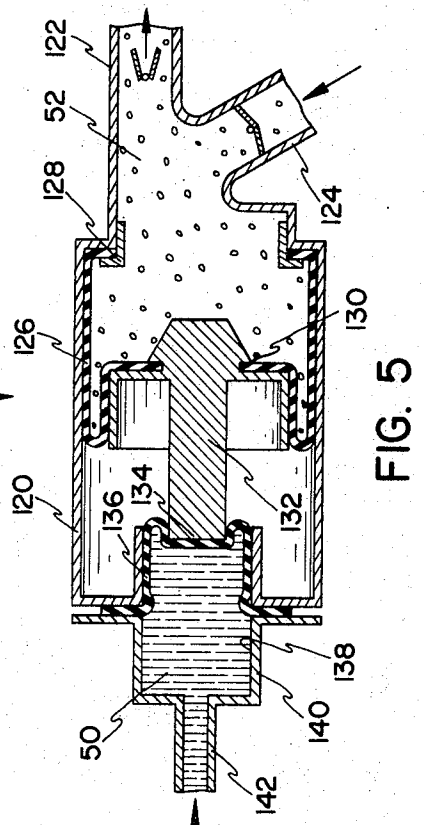

FIG. 5

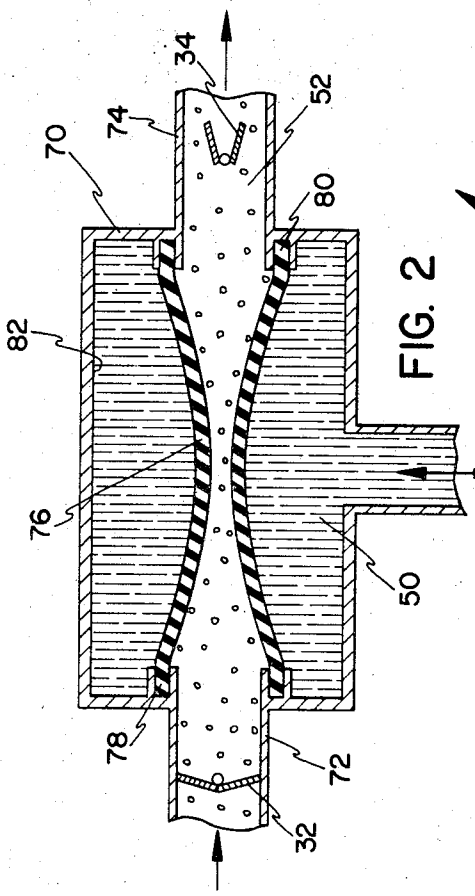

FIG. 2

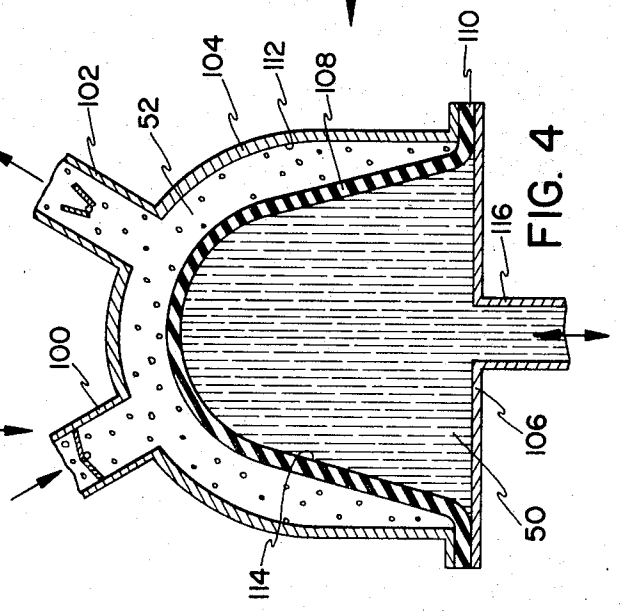

FIG. 4

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ARTIFICIAL HEART SYSTEM AND METHOD OF PUMPING BLOOD BY ELECTROMAGNETICALLY PULSED FLUID

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Int. Cl. A61f 1/24
U.S. Cl. 3—1 8 Claims

ABSTRACT OF THE DISCLOSURE

An artificial heart system including method and apparatus, the apparatus comprising, preferably, two interconnected ventricles, each internally provided with an accumulator diaphragm which is, according to the method, serially flexed in response to pulsatile displacement of electrically conductive fluid other than blood, the displacement being developed by an electromagnetic fluid driving device powered by thermoelectrically derived electrical energy.

The present invention relates to electromagnetic pumping systems and more particularly to electromagnetic pumping systems cooperating with ventricular structure for replacing or assisting a heart in its function of pumping blood through a living body.

In recent years considerable experimentation has been conducted to construct workable artificial heart pumps for replacing or assisting damaged or diseased hearts of living beings. Transplants of artificial hearts in animals have met with limited success, however, a self-contained, fully successful arificial heart has not, until this present invention, been devised.

Pumping devices utilizing moving parts have generated undesirable heat and have been susceptible to wear and deterioration. Electromagnetic pumps, with no mechanical moving parts, have not previously been generally accepted because the use thereof has depended largely upon passing electric current through the blood. See U.S. Pat. 3,206,768 in this regard. The passing of current through the blood generates undesirable amounts of heat within the blood because of the poor conductivity of the blood. Moreover, the low conductivity of the blood requires the use of high current densities which cause electrolysis of the blood. Difficulty has also occurred in developing suitable power sources which may be implanted within the body for long-term use without servicing or recharging. Many conventional artificial heart devices are powered by external sources of energy, such as compressed air, which greatly restrict the mobility of the user.

It is, therefore, a primary object of the present invention to provide an artificial heart system which alleviates or overcomes problems of the mentioned type.

The present invention utilizes an electromagnetic pump with no moving parts to pulse a conducting fluid other than blood. Preferably, the fluid is in simultaneous communication with two ventricles and is displaced by the electromagnetic pump alternately toward one or the other of the two ventricles. Volume changes in the ventricles are accommodated by flexing diaphragms or accumulators which control the volume of blood allowed within each ventricle and maintain a constant uniform blood volume in a natural body circulatory system. A long-life radioisotope thermoelectric power source adapted to be implanted within the chest cavity is used to supply energy to the electromagnetic pump.

Using the presently preferred apparatus and method of the invention, desirable pulsatile flow is achieved with complete compensation for blood volume changes. Undesirable heat and wear of moving mechanical parts is

eliminated. The problem of electrolysis and heat absorption in the blood are absent and complete mobility of the user is possible for long periods of time.

Accordingly, it is another primary object of the present invention to utilize an electrically conductive and heat conductive fluid, other than blood, for electromagnetic pumping in an improved artificial heart system.

It is another important object of the present invention to provide a novel system for pulsatilely pumping blood using an electromagnetic pumping device without moving parts.

Another and no less important object of the present invention is to provide a unique system for pulsatilely pumping blood using a biventricular system to compensate for blood volume changes.

A further and no less important object of the present invention is to provide a novel electromagnetic pumping device which is powered by a radioisotope thermoelectric source.

Another significant object of the present invention is to provide an improved artificial heart pump system capable of being implanted within the body.

These and other objects and features of the present invention will become more fully apparent from the following description and appended claims taken in conjunction with the accompanying drawings wherein:

FIG. 1 is a schematic representation of one presently preferred biventricular embodiment of the present invention; and

FIGS. 2–5 schematically illustrate other presently preferred embodiments of the ventricles illustrated in FIG. 1.

In the presently preferred embodiment of the invention, a biventricular system is illustrated. Although a monoventricular system could be used, the biventricular system is preferred because pulsatile pumping of blood normally requires a way of compensating for blood volume changes within the system. Pulsatile, rather than steady state, blood flow is desirable to enhance capillary perfusion, to prevent visco-elastic creep of the vessels and to operate the physiological baroreceptors.

Reference is now made to FIG. 1 wherein the biventricular artificial heart system generally designated 20 comprises ventricles **22** and **24**. Each of the ventricles **22** and **24** is substantially identical to the other, respectively comprising a rigid chamber **26**, **27** which is provided with an entrance port **28**, **29** and an exit port **30**, **31**. Each entrance port **28** and **29** is provided with a one-way valve **32** and **33** such as a Gott check valve. Similarly, each exit port **30** and **31** is provided with a one-way valve **34** and **35** which open in a direction opposite the valve **32**. Although Gott valves are shown in the illustrated embodiment, clearly any suitable one-way valve, such as a ball check valve could be used.

An accumulator diaphragm or resilient partition **36**, **37** is peripherally attached to the interior of the respective ventricles **22** and **24**, essentially central thereof, to divide each ventricle into two separate chambers **38**, **40** and **39**, **41**. Each accumulator **36**, **37** is preferably made of an inert, flexible material, such as silastic, a commercially available silicone rubber made by Dow-Corning Corporation.

Each entrance port **28**, **29** and each exit port **30**, **31** have exclusive communication with the respective chambers **38**, **39**. The chambers **40** and **41** in the ventricles **22** and **24** open into respective upper portions **42** and **44** of a generally U-shaped tube **46**. The tube **46**, thus, accommodates communication of the respective chambers **40** and **41** in the ventricles **22** and **24**.

An electrically conductive fluid **48**, such as mercury in the preferred embodiment, is confined, in part, by the tube **46**. If desired, a second fluid **50** may be located in the chambers **40** and **41** and the upper portion **42**

and 44 of the U-shaped tube above the mercury 48. The fluid 50 is preferably a biologically acceptable fluid, such as, for example, sterile isotonic saline solution. The purpose for the isotonic saline 50 is to prevent contamination of blood 52 located in chambers 38 and 39 in the event the accumulator 36 should rupture, develop a puncture or the like. Clearly, the saline solution 50 is merely a safety feature and is not essential to the apparatus or method comprising the present invention.

The lower portion 54 of the tube 46 carries an electromagnetic pump 56. It is presently preferred that a lightweight, easily portable or man-mobile Faraday type electromagnetic pump be used. In the illustrated embodiment, the mercury 48 is disposed in a thin walled duct 58 within the pump 56. Direct current is passed through a winding on a magnetic core (not shown) comprising part of the pump. The magnetic core is oriented so as to develop a magnetic field having one axis perpendicular to the direction of flow of the mercury 48 as shown by arrows 60 and 62. A voltage is impressed across the mercury 48 in a direction mutually perpendicular to the direction of flow of the mercury and the magnetic field. As a result, the mercury is caused to move axially in the direction of arrows 60 and 62 while the direct current is being conducted to the electromagnetic pump 56.

The direct current, needed by the pump 56, is generated by a thermoelectric power source 64. Energy for the thermoelectric power source 64 is preferably derived from radioisotope material such as, for example, promethium 147, made commercially available by Isochem, Inc., of Richland, Wash. Promethium 147 has a half-life of 2.62 years and a low energy decay requiring very little shielding and which provides the high current, low voltage output required by the electromagnetic pump. Although promethium 147 is presently preferred, any suitable radioisotope material having a relatively long half-life and low energy decay, including strontium 90, could be used. Moreover, other long-term electrical energy sources, such as chemical power supplies, biological fuel cells, muscle-power generators and the like are within the scope of this invention.

The direct current provided by the thermoelectric source is pulsed by a control device 66 which comprises capacitive elements and a standard conventional pacemaker system for pulsing the direct current to the thermoelectric source.

In the operation of the artificial heart system illustrated in FIG. 1, when the system has been implanted within a living being, direct current from the power source 64 is pulsed by the control device 66. The resulting pulsatile current is conducted to the electromagnetic driving mechanism 56. The mercury 48 is then moved in a direction mutually perpendicular to the flows of both the current and the electromagnetic field in the pumping mechanism 56, according to Faraday's Law. The accumulators 40 and 41 within the ventricles 22 and 24 are both caused to flex in the direction of flow of the mercury 48. The chamber 38 in ventricle 22 expands to receive blood 52 from the cardiovascular system of the living being, the valve 32 admitting the blood into the chamber 38. The chamber 39 decreases in size and blood 52 is forced out of the chamber 39 through the exit port 31, the valve 35 accommodating one-way movement of the blood out of the ventricle 24. Between pulses the mercury 48 will move in a direction opposite the arows 60 and 62 toward an equilibrium point due to the memory of the elastomeric accumulators 36 and 37 and the force of gravity upon the mercury 48. Movement of the mercury 48 in a direction opposite arrows 60 and 62 will cause the reverse effect, i.e. blood will flow into compartment 39 through the valve 33 and out of compartment 38 through the valve 34 until the next pulse is received by the pump 56.

Alternatively, the same pump or an adjacent substantially substantially identical pump could be used to forcibly move the mercury 48 in the opposite direction, thereby cyclically forcing the mercury 48 alternately toward the ventricles 24 and 22. The interval of alternation would be determined by the pacemaker (not shown) within the control device 66.

If desired, the ventricle illustrated in FIG. 2 can be used in place of the ventricles 22 or 24 illustrated in FIG. 1. With reference to FIG. 2, a cylindrically-shaped rigid element 70 is provided with an inlet port 72 and an outlet port 74. Each of the ports 72 and 74 is provided with one-way valves 32 and 34 which are substantially identical to valves 32 and 34 in FIG. 1. Inlet port 72 and outlet port 74 are connected by tube 76 sealed in fluid-tight relation at the ends 78 and 80 to the interior surface 82 of the element 70. The fluid 50, moved by the mercury 48 as described in FIG. 1, causes the tube 76 to collapse and squeezes the blood 52 contained therein through the outlet port 74. When the tube 76 returns to its normal cylindrical configuration, blood 52 is allowed to pass through the inlet port 72 into the tube 76.

FIG. 3 illustrates another preferred embodiment of a ventricle which may be used in place of the ventricles 22 and 24 of FIG. 1. In the embodiment of FIG. 3, inlet port 86 and outlet port 88 are disposed in a substantially flat element 90. A bell-shaped member 92 cooperates with the element 90 to form a rigid ventricle. An accumulator 94 is peripherally attached at 95 between the element 90 and the member 92 in fluid-sealed relation, thus forming two separate accumulator chambers 96 and 98. The accumulator chamber 98 is in free communication with fluid 50 through the tube 97. When the fluid is forced into the chamber 98, the accumulator 94 collapses forcing blood 52 out through the outlet port 88. When fluid 50 is withdrawn from the chamber 98, the chamber 96 is filled with blood through the inlet port 86.

FIG. 4 illustrates still another embodiment of a ventricle which may be used in place of the ventricles 22 and 24 illustrated in FIG. 1. With reference to FIG. 4, inlet port 100 and outlet port 102 are disposed in the essentially bell-shaped member 104. The bell-shaped member 104 cooperates with an essentially flat element 106 to form a rigid ventricle. The ventricle is internally provided with an accumulator 108 which is fluid-sealed at the periphery 110 between the member 104 and the element 106. The acumulator 108 forms accumulator chambers 112 and 114. When accumulator chamber 114 expands due to the influx of fluid 50 through the tube 116, blood 52 is forced out of the outlet port 102 and, conversely, when the accumulator chamber 114 decreases in size due to the egress of fluid 50 through the tube 116, blood will enter the accumulator chamber 112 through the inlet port 100.

FIG. 5 schematically illustrates a differential piston pump which may be used in place of the ventricles 22 and 24 of FIG. 1. In FIG. 5, a rigid casing 120 is provided with outlet port 122 and inlet port 124. A rolling diaphragm 126 is fluid-sealed at one end 128 to the casing 120 and, likewise, fluid-sealed at the other end 130 to a differential piston 132. The trailing end of the piston is in contact with a high-pressure rolling diaphragm 136 fluid-sealed at the exterior of the casing 120. The diaphragm 136 forms a chamber 138 with a fluid-carrying coupling 140 which is continuous with tube 142.

Fluid 50 entering the chamber 138 through the tube 142 forces the piston 132 to advance toward the inlet and outlet ports 124 and 122, respectively. As the differential piston 132 moves, the rolling diaphragm 126 rolls upon itself and blood 52 is forced out through the outlet port 122. Conversely, when fluid 150 egresses through tube 142, the differential piston 132 will move in the opposite direction causing the diaphragm 136 to roll upon itself and blood will move through the inlet port 124.

It should now be appreciated that the present invention provides a new and useful apparatus and technique for pumping blood in connection with or in place of the

heart of a living being. Electromagnetic pumping of a conducting fluid other than blood reduces heat generation in the blood and substantially eliminates electrolysis thereof. The provision of a long-life radioisotope energy source used in connection with a lightweight thermoelectric generator makes implantation of the artificial heart system within the body of the living being practical.

The invention may be embodied in other specific forms without departing from the spirit or essential characteristics thereof. The present embodiments are, therefore, to be considered in all respects as illustrative and not restrictive, the scope of the invention being indicated by the appended claims rather than by the foregoing description, and all changes which come within the meaning and range of equivalency of the claims are therefore to be embraced therein.

What is claimed and desired to be secured by United States Letters Patent is:

1. An artificial heart pump apparatus comprising electrically conductive fluid other than blood and ventricle means having accumulator means disposed therein responsive to pulsatile displacement of the electrically conductive fluid, the accumulator means comprising at least one resilient partition defining two chambers the peripheral edge of the partition being joined to the ventricle means in fluid tight relation, one chamber and one surface of the partition adapted to be disposed in pressure communication and contact with circulated blood obtainable from the cardiovascular system of a living body, the other chamber and a second opposed surface of the partition being in pressure communication with the electrically-conductive fluid, electromagnetic means for exposing said electrically-conductive fluid to a magnetic field caused by the electromagnetic means to exert a pulsating force on and cyclically displace the electrically-conductive fluid thereby causing the conductive fluid to cyclically exert pressure upon the second surface of the partition in the other chamber, and ingress and egress valve means adapted to be placed in fluid communication with the cardiovascular system for successively receiving and emitting substantially equal volumes of blood to and from the one chamber of the ventricle means in response to back and forth displacement of the partition.

2. In an apparatus as defined in claim **1** wherein said ventricle means comprise interconnected biventricular structure, the two parts of said biventricular structure being in simultaneous communication one with the other linked by the electrically-conductive fluid, each of the two parts of the biventricular structure being provided with separate accumulator structure each defining the two chambers, adapted to serially exert increased pressure on the blood to respectively simultaneously expel and draw equal volumes of blood from and to the one chambers of the accumulator structure, thereby maintaining a uniform blood level for use within the cardiovascular system.

3. An artificial heart pump comprising in combination: thermoelectric power source means for generating electrical energy, means for pulsing the flow of electrical energy from the source means, confined electrically conductive fluid, electromagnetic driving means responsive to the pulsed flow of electrical energy for pulsatilely pumping the confined electrically-conductive fluid by magnetic energy without the use of mechanically moving parts, dual ventricles each comprising accumulator means adapted to separate blood on one side from at least one other fluid subject to pressure caused by the action of the electrical energy confined within fluid communication means and disposed on the other side of the accumulator means, said accumulator means responding to changes in pressure exerted by the confined electrically-conductive fluid when influenced by electrical energy, and one-way valve means for selectively controlling the flow of the blood in and out of the ventricles.

4. In a heart pump as defined in claim **3** where in the thermoelectric power source means comprises a man-mobile, long-term radioisotope thermoelectric power source.

5. In a heart pump as defined in claim **3** further comprising an isotonic, biologically compatible liquid interposed between the electromagnetic driving means and the accumulator means.

6. In a method of pumping blood within a living body by cyclically exposing an electrically-conductive fluid to an electromagnetic field, thereby pulsing the electrically-conductive fluid which is in pressure-communication with one side of a deformable accumulator partition of sheet material, flexing the central interior of the sheet accumulator partition in response to the pulsatile pressure exerted by the electrically-conductive fluid, imposing the pulsatile pressure on the blood across the sheet partition which blood is in communication with the other side of the deformable sheet accumulator partition and displacing the blood in response to the fluid pressure in a direction pre-defined by check valves.

7. A method of pumping blood through a ventricular artificial heart apparatus used by a living body comprising the steps of: providing a source of electrical current, pulsatilely exposing electrically conductive liquid to the electrical current to pulsatilely pump the electrically conductive liquid to impose a series of pressure pulses upon one side of an accumulator diaphragm comprising part of the artificial heart apparatus, flexing the accumulator diaphragm responsive to the pressure pulses of the electrically-conductive liquid, and cyclically receiving and emitting blood adjacent the other side of the accumulator diaphragm, maintaining an essentially constant uniform blood volume within the cardiovascular system of the living body according to the motion of the flexing accumulator.

8. A method as defined in claim **7** wherein the pulsatilely exposing step is responsive to a conversion of thermal energy emitted by a radioisotope source to electrical energy.

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60—54.5; 128—1; 417—389, 395, 411