

[54] **MAGNETICALLY ACTUATED PUMP WITH FLEXIBLE MEMBRANE**

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3,733,616.

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[51] Int. Cl. ... F04b 17/00, F04b 35/00, F04b 43/00

[58] Field of Search 417/412, 413, 322;
3/1, DIG. 2; 128/214 R, 273, 1 D

[56]

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Primary Examiner—Carlton R. Croyle

Assistant Examiner—Richard Sher

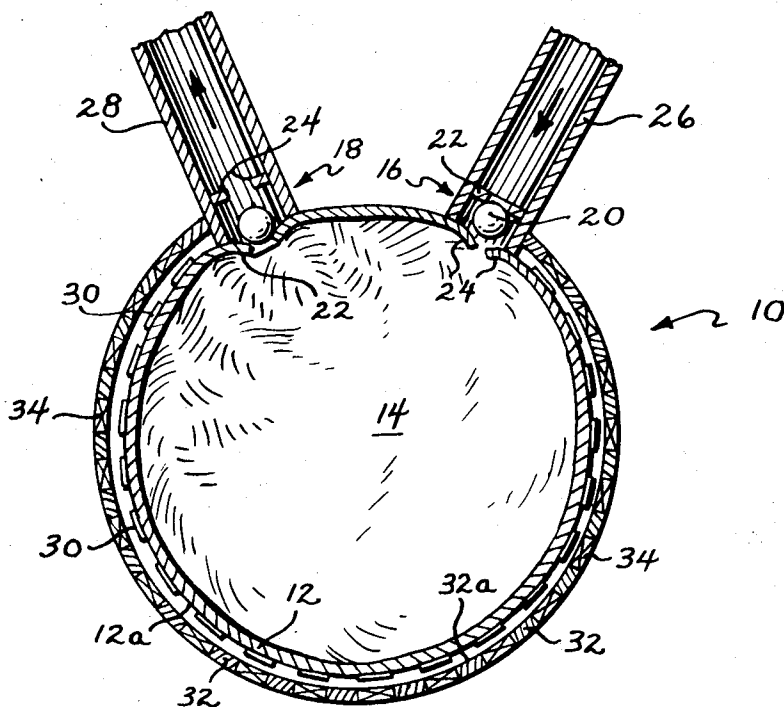
Attorney—C. Yardley Chittick et al.

[57]

ABSTRACT

An electromagnetic pump which utilizes a plurality of electromagnets to alternately repel and attract a corresponding plurality of permanent magnets mounted on a flexible membrane which forms the pumping chamber.

6 Claims, 6 Drawing Figures



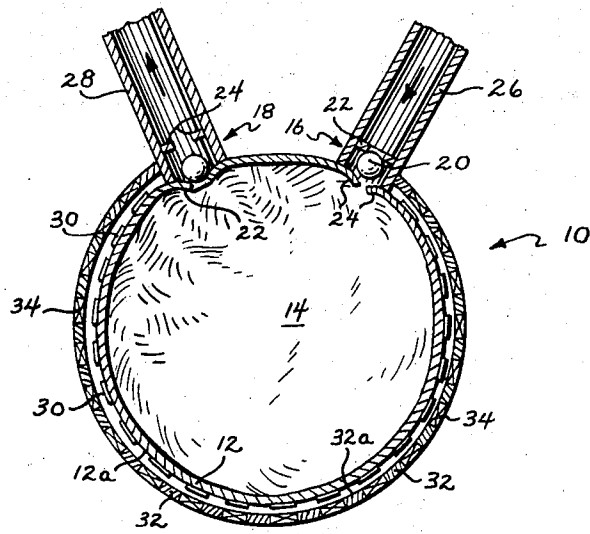


FIG. 1

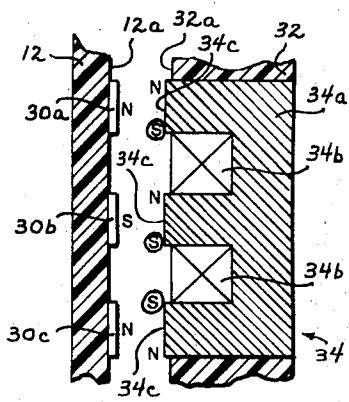


FIG. 2

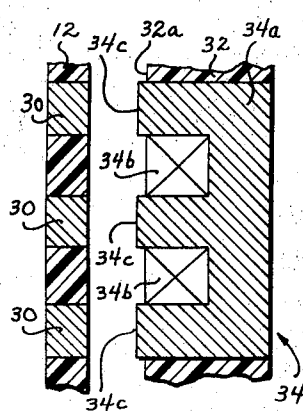


FIG. 3

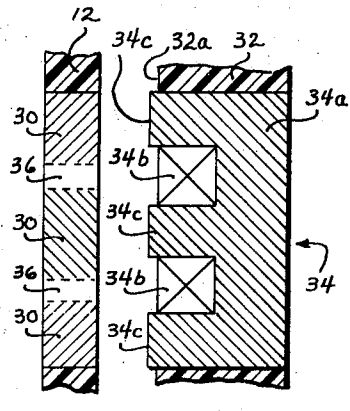


FIG. 4

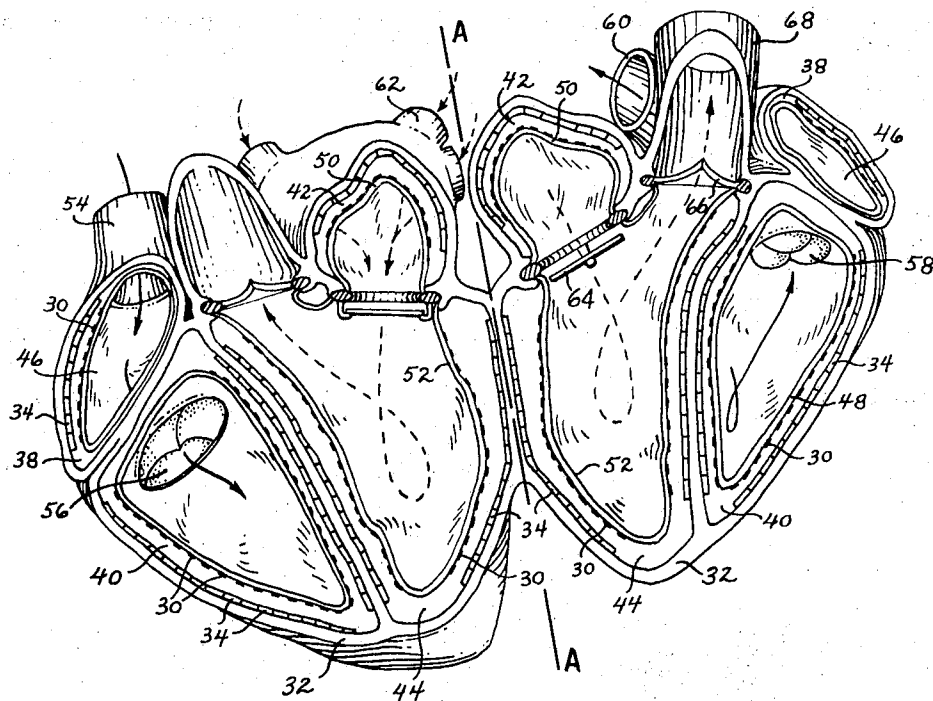


FIG. 5

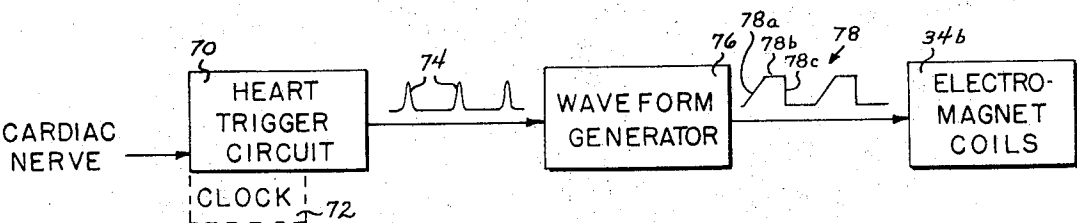


FIG. 6

MAGNETICALLY ACTUATED PUMP WITH FLEXIBLE MEMBRANE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a division of my copending application Ser. No. 139,701 filed May 3, 1971 for ARTIFICIAL HEART now U.S. Pat. No. 3,733,616 issued May 22, 1973.

BACKGROUND OF THE INVENTION

This invention relates to artificial hearts in general, and more particularly, to an artificial heart which duplicates as closely as possible the functional aspects of the human heart.

Considerable effort has been expended in recent years to develop a substitute for the human heart. Representative examples of recent technology in the field of implanted pumps are found in the following U.S. Pat. Nos. 3,182,335; 3,206,768; and 3,327,322. Various other types of blood pumps for external use have been described in U.S. Pat. Nos. 2,815,715; 2,971,471; and 3,021,793. To date, no known pumping system adequately duplicates the heart's pumping action within a volume which would permit implantation of the pumping system in the human body.

It is accordingly, a general object of the present invention to provide an artificial heart for implantation in the human body which duplicates as closely as possible the operation of the human heart.

It is a specific object of the present invention to provide an artificial heart which occupies substantially the same volume as the human heart.

It is another object of the present invention to provide an artificial heart which minimizes the mechanically induced damage to the blood caused by the pumping action of the artificial heart.

It is a feature of the present invention that the materials employed in the artificial heart are readily available and compatible with the human body.

It is still another feature of the present invention that the artificial heart does not require excessive electrical power so that a light, compact power source can be employed.

These objects and features and other objects and features of the present invention will best be understood by a detailed description of a preferred embodiment thereof, selected for purposes of illustration and shown in the accompanying drawings in which:

FIG. 1 is a generalized, diagrammatic view in cross-section of a single chamber pump illustrating the basic components of the artificial heart pump;

FIG. 2 is an enlarged view in cross-section showing a portion of the blood containing, flexible membrane wall together with the permanent magnets mounted thereon and the associated electromagnets;

FIG. 3 is a similar view to that of FIG. 2 showing another arrangement for the membrane wall and permanent magnets;

FIG. 4 is still another view similar to that of FIG. 2 showing an alternative embodiment of the membrane in which the membrane is filled with discrete magnetized particles;

FIG. 5 is a view in perspective of the artificial heart split open along line A—A in FIG. 5; and,

FIG. 6 is a view in block form showing the associated electrical circuitry for the artificial heart pump's electromagnets.

Turning now to the drawings and particularly to FIG. 1 thereof there is shown in generalized diagrammatic view a single chamber pump constructed in accordance with the present invention and indicated generally by the reference numeral 10. The pump 10 comprises a flexible bag or membrane 12 which defines a fluid containing chamber 14. Unidirectional inlet and outlet fluid valves 16 and 18, respectively, are provided for the pump chamber 14. For purposes of illustration, the inlet and outlet valves shown in FIG. 1 are depicted as ball check valves having a moveable ball 20 which seats against valve seats 22 in the closed direction and is held within the valve in the open condition by check valve ball retaining members 24. However, it should be understood that other valve configurations can be employed for inlet and outlet valves 16 and 18. Conduit means 26 and 28 are employed to connect the pump chamber 14 through the inlet and outlet valves respectively to a source of pumped fluid (not shown) and to utilization means (not shown) for the fluid pumped out of the chamber 14.

In the preferred embodiment, the flexible bag 12 is formed from a plastic material or from a rubber latex. Existing technology has provided suitable plastics and latex materials which are compatible with human blood. A plurality of magnetic poles 30 are formed on the exterior surface 12a of the flexible bag. Preferably, the magnetic poles comprise separate permanent magnets that are affixed to the exterior surface of the flexible bag 12, as shown in greater detail in FIG. 2. Other structural configurations for forming the magnetic poles 30 on the exterior surface of the flexible bag 12 are illustrated in FIGS. 3 and 4 and will be described below in greater detail. For the moment, it is sufficient to note that the magnetic poles 30 are oriented in a predetermined pattern of magnetic polarities.

Surrounding at least a portion of the flexible bag 12 is a "rigid" support means or shell 32 which contains a corresponding plurality of electromagnets 34. The electromagnets 34 are positioned on shell 32 so that the electromagnetic fields generated by the electromagnets 34 will interact with the corresponding flexible bag magnetic poles 30. Assuming for purposes of illustration that the magnetic poles 30 on the flexible bag 12 have a fixed plurality, as would be the case with permanent magnets, it can be seen that when the electromagnets 34 are energized by a current flow in one direction, the magnets 30 will be repelled from the electromagnets 34 and, conversely, when the electromagnets are energized in the reverse direction, the magnets 30 will be attracted to the electromagnets 34.

If the support means or shell 32 is sufficiently "rigid" to resist the repulsion and attraction forces generated by the interaction of the electromagnetic and magnetic fields of electromagnets 34 and magnets 30, it can be seen that the flexible bag 12 will be compressed when the magnets 30 are repelled from the electromagnets and expanded outwardly when the magnets are attracted to the electromagnets.

The term "rigid" as used in the description and in the claims covers any substance or material which has sufficient rigidity to resist the forces generated by the interaction of the electromagnetic and magnetic fields. Expressed in a slightly different way, the shell should

remain stationary while the flexible bag moves away from or toward the shell under the influence of the interacting magnetic fields. It will be appreciated that this definition of the term "rigid" covers many items which would normally not be considered "rigid" and that the term is relative given the various operating parameters e.g., electromagnetic and magnetic field strengths, of the pump.

In order to maximize the effectiveness of the magnetic repulsion forces, it is desirable to have the exterior surface 12a of the flexible bag touching the inner surface 32a of the support means or shell 32 with the corresponding magnets 30 and electromagnets 34 in abutting relationship. Thus, in the rest or neutral condition, the flexible bag 12 will be in substantial contact with the inner surface 32a of the exterior shell 32.

Given the structural and electrical configuration depicted in FIG. 1, it will be appreciated that if the flexible bag chamber 14 is filled with a fluid, such as, blood, when the electromagnets 34 are energized to cause repulsion of the permanent magnets 30, the flexible bag 12 will be compressed thereby forcing the fluid within chamber 14 out through the unidirectional outlet valve 18 into outlet conduit 28. At the end of the compression stroke, the bag can be returned to its rest position by reversing the current flow through the electromagnets 34. However, in many instances, it is not necessary to provide a current reversal through the electromagnets 34 in order to return the flexible bag to its uncompressed, rest condition as shown in FIG. 1. For example, if the flexible bag 12 is constructed from a resilient material, it will return to its rest or neutral condition automatically. The return of the flexible bag 12 to the rest condition is further assisted in an inlet gravity flow system by the force of gravity pulling the fluid in inlet conduit 26 through the inlet unidirectional flow valve 16. This situation occurs in the normal human heart and is utilized in the artificial heart illustrated in FIG. 5.

FIGS. 2 through 4 illustrate, in greatly enlarged form, a portion of the flexible bag 12, the magnetic poles 30 and the electromagnets 34. Looking at FIG. 2, the flexible bag 12 has three permanent magnets 30a, 30b, and 30c secured by appropriate means such as for instance, adhesive, to the exterior surface 12a of the flexible bag. The electromagnet 34 is shown in greater detail and comprises a core portion 34a and coil windings 34b. Preferably, the electromagnetic coils 34 are mounted within the shell 32 and flush with the inner surface 32a thereof. The physical arrangement of the magnetic poles 30 is governed by the particular configuration of the electromagnet poles 34c. The magnetic polarity arrangement between the magnetic poles 30 and the electromagnetic poles 34 is designed to provide a uniform repulsion or attraction between the magnetic and electromagnetic fields established thereby.

For purposes of illustration, the polarity of the magnetic poles 30 has been arbitrarily shown in the sequence of north, south, north which is indicated in FIG. 2 by the small letters, "N", "S", "N". The corresponding electromagnetic polarities for the electromagnetic poles 34c are shown by similar small letters. In this configuration, it can be seen that the flexible bag magnet poles 30 will be repelled from the corresponding electromagnet poles. The converse or attraction condition is shown in FIG. 2 by the North and South polarity indications within a circle.

FIG. 3 illustrates an alternative construction for the mounting of the magnets 30 with respect to the flexible bag 12. As shown in FIG. 3, the magnets 30 are mounted within the flexible bag wall and, preferably, with the exterior surfaces thereof flush with the exterior surface 12a of the flexible bag. If plastic or latex materials are employed for fabricating the flexible bag 12, the magnets 30 can be directly molded in the wall of the flexible bag.

FIG. 4 illustrates still another method for forming the magnetic poles on the exterior surface of the flexible bag 12. In this instance, the flexible bag 12 acts as a binder for a plurality of discrete magnetizable elements such as ferromagnetic filings. The technology of metal filled plastics is well known at the present time and need not be discussed in any further detail. One currently available material which is satisfactory for the pump of the present invention is an iron filled plastic sold by the 3M Company under the tradename "Plastiform." Unlike the case of separate magnets, as shown in FIGS. 2 and 3, the use of magnetized discrete elements within a binder, as shown in FIG. 4, does not produce sharp transitions between the magnetic polarities. Thus, as shown in FIG. 4, there is a transition region 36, between each magnetic polarity. This transition is indicated by the dotted lines between the magnetic polarities.

Although the preceding discussion in connection with FIGS. 1 through 4 has focused upon the use of magnetic poles and, preferably, permanent magnets on the exterior surface of the flexible bag 12, conceptually, it is possible to use electromagnets on the flexible bag 12. Conversely, the magnetic fields for the support means or outer shell 32 can be generated by permanent magnets. However, this configuration is generally undesirable for an artificial heart because of the increased weight of the electromagnets and associated wiring on the flexible bag 12 and the concomitant complexity of providing electrical connections to the moveable flexible bag 12. Therefore, it is recommended that in the case of an implantable artificial heart, the permanent magnet-flexible bag configuration with electromagnets on the exterior shell be employed.

Having described the generalized concepts of the pump of the present invention, I will now describe in detail an artificial heart which utilizes magnetic field interaction to provide a pumping action which very closely duplicates the functional aspects of the human heart. FIG. 5 is a view in perspective of an artificial heart constructed in accordance with the present invention and split open along line A—A. For purposes of clarity, certain elements of an actual human heart have been omitted from the FIG. 5. However, the omitted elements are not necessary for the operation or understanding of the artificial heart. The major elements of the artificial heart are depicted in FIG. 5 and will be discussed below. To one skilled in the art, it will be apparent that the structural elements illustrated in FIG. 5 will provide a substitute for the human heart which can be connected to the existing blood conduits by well known and currently available surgical techniques.

Referring now to FIG. 5, the "rigid" support means of shell 32 is formed in a generally cardioid shape with the interior sections thereof defining a plurality of chambers which correspond to the major chambers within a human heart. Positioned within each chamber is a flexible bag corresponding to the flexible bag 12 il-

illustrated in FIG. 1 and discussed above. For purposes of identification in connection with the following description of FIG. 5, separate reference numerals will be used for each shell-formed chamber and corresponding flexible bag. The artificial heart shown in FIG. 5 has been split along an axis A—A which represents generally the axis of symmetry for the heart. The left hand section of the outer shell 12 forms portions of four separate chambers, namely, a right atrium chamber 38, a right ventricle chamber 40 and a left atrium chamber 42 and a left ventricle chamber 44. In a corresponding manner, the right hand section of the outer shell 12 also forms portions of the right atrium chamber 38, right ventricle chamber 40, left atrium chamber 42, and left ventricle chamber 44.

Positioned within each of these chambers in the preferred embodiment of the artificial heart, is a corresponding flexible bag i.e., a right atrium bag 46, a right ventricle bag 48, a left atrium bag 50, and a left ventricle bag 52. The right and left atria bags 48 and 50 can be omitted, if desired, but they are recommended in order to duplicate as closely as possible the operation of the human heart. Each of the flexible bags is provided with a plurality of magnetic poles 30 shown representationally in FIG. 5. Similarly, each of the outer shell chambers 38, 40, 42 and 44, is provided with a corresponding plurality of electromagnets 34, which are also shown representationally in FIG. 5.

The fluid or blood flow paths through the artificial heart corresponds to the fluid paths within the human heart. Looking at the left hand side of FIG. 5, blood enters the right atrium bag 46 through an upper vena cava 54 and a lower vena cava (not shown). When the electromagnets on the right atrium inner shell surface 38 are energized, the right atrium bag 46 is compressed forcing the blood therein through a unidirectional inlet valve, such as cusp valve 56, and into the right ventricle flexible bag 48. In similar fashion, the right ventricle bag is compressed to force the blood therein out through another unidirectional valve 58 into the pulmonary aorta 60 to the lungs (not shown). The oxygenated blood from the lungs returns to the heart through pulmonary vein 62 and enters the left atrium flexible bag 50. Upon compression of the left atrium flexible bag, the blood therein is forced through a unidirectional valve such as flat plate valve 64 into the left ventricle bag 52. Subsequent compression of the left ventricle bag 52 forces the blood outwardly through another unidirectional valve 66 into the systemic aorta 68. Although cusp and flat plate valves have been shown in FIG. 5, these types of valves are merely illustrative and other types of unidirectional valves can be used in the artificial heart.

It will be appreciated from the preceding description that the fluid flow paths within the artificial heart shown in FIG. 5 duplicate the corresponding blood flow paths through the human heart. By properly energizing the electromagnets 34, a uniform compression over a volume of liquid is obtained without scraping or local compressive peaks. The field action of the cardiac muscle is approximated in the artificial heart of the present invention by a uniform magnetic field that is applied to the pumping chamber bags 12.

In the preferred embodiment, the flexible bags 12 generally and reference numerals 46, 48, 50 and 52, specifically, carry an external permanent magnetic field either through magnets attached to the outside

surface of the bag or by direct magnetic imprinting as depicted in FIG. 4. The outer shell 12 contains a corresponding number of electromagnets 34 in close proximity to the flexible bags. Preferably, in the relaxed position as noted above, each of the flexible bag magnets is in abutting relationship to the corresponding electromagnet in order to maximize the magnetic forces generated by the interaction of the electromagnet and permanent magnet fields. To compress any one of the flexible chamber bags, it is only necessary to activate the desired electromagnetic coils to produce the same polarity as the polarity of the abutting flexible bag magnets. Since there is no direct conversion of electrical to mechanical energy, there are no moving parts to wear out. The only motion is in the flexible bags, and therefore, an extremely favorable meantime between failures can be achieved.

One of the advantages of the pumping system of the present invention is the ability to utilize both poles of an electromagnet. Looking at FIG. 5, it can be seen that for a major distance, the left and right ventricle flexible bags 52 and 50, are in a side-by-side relation. Therefore, by providing each flexible bag with a single magnetic polarity and by making the magnetic polarities of the two adjacent bags opposite, it is possible to obtain the appropriate interaction of the magnetic and electromagnetic fields to produce a repulsion force i.e., compression of the bags, with a single electromagnet.

The control circuitry for energizing the electromagnets 34 is readily available in current electro-cardiac technology. Looking at FIG. 6, there is shown in block form the timing and waveform generating circuitry for energizing the electromagnetic coils of the artificial heart. The initial timing signals are obtained from a heart trigger circuit 70 now generally known under the generic term of a "pacemaker." The pacemaker 70 can be triggered by signals from the cardiac nerve or by a separate internal clock 72. The output of the pacemaker 70 comprises a pulse train of relatively sharp pulses 74. The pulses 74 are converted by a waveform generator 76 into a waveform 78 having a relatively steep ramp portion 78a, a plateau portion 78b and a sharp trailing edge 78c. The general shape of the pulse waveform, the repetition rate and the pulse duration can be adjusted to accommodate the particular electrical circuitry of the artificial heart and to produce the desired pumping action.

On the basis of current electro-cardiac technology, it is believed that the waveform shown in FIG. 6 will produce the closest approximation of the human heart pumping action. Specifically, it is desirable to duplicate the isovolumetric compression of the human heart which produces the readily discernable pumping or "beat" action of the human heart. To this end, the cusp valves 56 and 66 in the artificial heart depicted in FIG. 5 are preloaded in the closed position and will not open until a predetermined pressure has been reached. Using the waveform 78 shown in FIG. 6, the electromagnet coils 34d provide a rapid build-up of the magnetic repulsion along the steep leading edge of the voltage waveform and a constant pressure along the plateau of the waveform.

The power requirements for the electrical circuits shown in FIG. 6 are relatively low and can be supplied by a number of sources including an externally carried lightweight battery belt, a biological battery, or by a scaled-up version of the atomic thermocouple pace-

maker power source which has been developed by the National Institute of Health.

Having described in detail the preferred embodiment of my artificial heart, it will be appreciated that the artificial heart closely duplicates the functional aspects of the human heart. Specifically, it can be seen that unlike piston and other reciprocatory pumps, no mechanical abrasive forces are exerted upon the blood. Furthermore, turbulence is minimized and the blood is subjected only to the normal compressive actions found in a human heart.

Although the artificial heart depicted in FIG. 5 duplicates each of the four chambers of the human heart, i.e., the left and right atria and the left and right ventricles, the basic pumping action can be achieved by using only two pumping chambers corresponding to the left and right ventricles. However, in order to minimize the deleterious effects created by the pumping shock wave it is desirable to interpose between the artificial heart and the normal body blood conduits a mechanical equivalent of the human left and right atria. Therefore, it is recommended that the artificial heart be constructed in accordance with the chamber configuration shown in FIG. 5. The use of corresponding left and right atria flexible bags is also preferable, as mentioned previously. However, it should be understood that the present invention is not limited to a four chamber artificial heart, but instead can be constructed, if desired, with only two chambers.

From the preceding detailed description of a preferred embodiment of my invention, it will be appreciated that various modifications can be made therein without departing from the scope of the invention as defined in the appended claims.

Therefore, what I claim and intend to secure by Letters Patent of the United States is:

1. A chamber pump comprising:
 1. a flexible bag which defines a fluid containing chamber;
 2. inlet and outlet unidirectional fluid valve means

- fluidly coupled to said flexible bag chamber;
3. means forming a plurality of magnetic poles on the exterior surface of said flexible bag;
4. rigid support means surrounding at least a portion of said flexible bag;
5. a plurality of magnetic means positioned on said support means for generating magnetic fields which interact with the magnetic fields of said magnetic poles.
2. A chamber pump comprising:
 1. a flexible bag which defines a fluid containing chamber;
 2. inlet and outlet unidirectional fluid valve means fluidly coupled to said flexible bag chamber;
 3. means forming a plurality of magnetic poles on the exterior surface of said flexible bag;
 4. rigid support means surrounding at least a portion of said flexible bag;
 5. a plurality of electromagnetic means positioned on said support means for generating electromagnetic fields which interact with the magnetic fields of said magnetic poles; and,
 6. means for energizing said electromagnetic means.
3. The pump of claim 2 further characterized by said energizing means energizing said electromagnetic means to cause repulsion between said electromagnetic and magnetic fields.
4. The pump of claim 2 further characterized by said energizing means cyclically energizing said electromagnetic means to alternately cause attraction and repulsion between said electromagnetic and magnetic fields.
5. The pump of claim 2 wherein said means forming a plurality of magnetic poles on the exterior surface of the flexible bag comprises a plurality of permanent magnets.
6. The pump of claim 2 further characterized by said outlet unidirectional fluid valve means being preloaded to open when a predetermined pressure is reached.

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